

LARGE-SCALE SECURITY CONSTRAINED OPTIMAL REACTIVE POWER FLOW FOR OPERATIONAL LOSS MANAGEMENT ON THE GB ELECTRICITY TRANSMISSION NETWORK

A thesis submitted in partial fulfillment for the
degree of Engineering Doctorate

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by

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Abstract

The transmission of power across the GB transmission system, as operated by National Grid, results in inevitable loss of electrical power. Operationally these power losses cannot be eliminated, but they can be reduced by adjustment of the system voltage profile. At present the minimisation of active power losses relies upon a lengthy manually based iterative adjustment process. Therefore the system operator requires the development of advanced optimisation tools to cope with the challenges faced over the next decade, such as achieving the stringent greenhouse gas emission targets laid down by the UK government, while continue to provide an economical, secure and efficient service.

To meet these challenges the research presented in this thesis has developed optimisation techniques that can assist control centre engineers by automatically setting up voltage studies that are low loss and low cost. The proposed voltage optimisation techniques have been shown to produce solutions that are secured against 800 credible contingency cases. A prototype voltage optimisation tool has been deployed, which required the development of a series of novel approaches to extend the functionality of an existing optimisation program. This research has lead to the development of novel methods for handling multi-objectives, contradictory shunt switching configurations and selecting all credible contingencies. Studies indicate that a theoretical loss saving of 1.9% is achievable, equivalent to an annual emissions saving of approximately 64,000 tonnes of carbon dioxide.

A novel security constrained mixed integer non-linear optimisation technique has also been developed. The proposed method has been shown to be superior to several conventional methods on a wide range of IEEE standard network models and also on a range of large-scale GB network models. The proposed method manages to further reduce active power losses and also satisfies all security constraints.

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Abbreviations

AC	Alternating Current
ACS	Averaged Cold Spell
AHP	Analytic Hierarchical Process
AVR	Automatic Voltage Regulator
BETTA	British Electricity Trading Transmission Arrangements
BM	Balancing Mechanism
BSC	Balancing and Settlement Code
DC	Direct Current
DNO	Distribution Network Operator
ENCC	Electricity National Control Centre
ENGD	Engineering Doctorate
FACTS	Flexible AC Transmission System
GSP	Grid Supply Point
LCPD	Large Combustion Plant Directive
LP	Linear Programming
MINLP	Mixed Integer Non-Linear Programming
NETA	New Electricity Trading Arrangements
OPF	Optimal Power Flow
ORPF	Optimal Reactive Power Flow
PNA	Power Network Analyzer
SCOPE	Security Constrained Optimisation Program Engine
SCORPF	Security Constrained Reactive Optimal Power Flow
SE	State Estimator
SHETL	Scottish Hydro Electricity Transmission
SLP	Sequential Linear Programming
SPT	Scottish Power Transmission
SQSSS	Security and Quality of Supply Standards
SVC	Static VAr Compensator
TAE	Transmission Analysis Engineer
TDE	Transmission Dispatch Engineer

TLF	Transmission Losses Factor
TLM	Transmission Losses Multiplier
TNEP	Transmission Network Expansion Planning
TR	Transmission Requirements
VAr	Volts Ampere Reactive
VCI	Voltage Control Improvement
VOCs	Volatile organic compounds

Executive Summary

Introduction

Reactive power management is a key process in the secure and low loss operation of the transmission network that will become even more crucial as Great Britain (GB) adapts to meet the carbon emission targets laid down by the Climate Change Act of 2008. At present reactive control is undertaken by manually issuing actions, which include the despatch of generation to target reactive power output and the switching of reactive compensation plant. This research is focussed on the development of methods that will enable the automation of reactive power control at the GB Electricity National Control Centre. This technology will enable an improvement in the management of active transmission losses, which is the difference between energy from generators going into the transmission network and demand taking energy out of the transmission system.

Security Constrained Optimal Reactive Power Flow

The development of a reactive despatch advice tool requires the accurate modelling, and the efficient determination of a solution, to the GB transmission network Security Constrained Optimal Reactive Power Flow (SCORPF) problem. The operational SCORPF problem can be formulated as the general mathematical problem of finding the optimal operational network plan of a power network, while meeting all the relevant operational feasibility and security requirements. The SCORPF model needs to be sufficiently constrained in order to ensure that the solution meets the GB Security and Quality of Supply Standards. These standards place specific requirements on bus bar voltage limits and voltage changes following a single or double circuit contingency event, which means that all credible contingency events should be included in the SCORPF model. The SCORPF model also needs to specify the independent control variables for which optimal values need to be determined. The SCORPF solution process securely minimises an objective function, in most cases this is the total active transmission losses. The SCORPF proceeds by initially solving the power flow and contingency analysis, the problem is then linearised around the current operating point and a compact LP solver is utilised to determine an operating point that is

slightly closer to the final solution. This process is repeated iteratively until a termination criterion is satisfied, such as all control changes are less than a tolerance value.

Current Limitations of SCORPF technology

Practical implementation of SCORPF in an electricity control centre is difficult to achieve, because of the requirements on both the modelling to adequately capture all of the constraints and the SCORPF algorithm to find a solution in a robust and transparent manner. For example in the mid-1990s National Grid, the GB electricity transmission system operator, implemented an operational SCORPF tool called ACCORD. While initial user experience of using ACCORD was described as favourable, it was limited by the number of contingency cases that could be included in the model. This was one of the limitations that eventually resulted in ACCORD being withdrawn from service. While there is a wide range of literature on small scale ORPF studies there is limited literature on the subject of practical implementations of SCORPF, which is reflected in the industrial use of SCORPF tools.

One reason for the shortage of practical SCORPF tools maybe due to the sub-optimal solution methods that are utilised to solve the mixed integer optimisation problem involving large switchable shunt devices. Many large scale SCORPF approaches treat these shunt devices as continuous variables during the main optimisation, and at the end of the final iteration they are rounded to their nearest discrete value. This rounding potentially degrades optimality and increases the risk of solution infeasibility. To the best of the author's knowledge there is no method presented in the literature that is able to provide an accurate and rapid solution to this large scale SCORPF problem. The reason for this is that the problem by its very nature is non-deterministic (NP) complete, which means that it is almost certain that finding the global minimum will be extremely challenging to compute efficiently.

Aims and Objectives

The long-term aim of the general research area is to overcome barriers preventing the wide spread use of practical SCORPF based voltage scheduling. The main objective of the research, which is consistent with this aim, is to build confidence among engineers in practical SCORPF technologies that could be implemented in a control centre environment to enable the implementation of secure low loss network solutions. By developing voltage scheduling methods that prove themselves in the short-term, longer term implementation objectives should become achievable. The specific objectives of the research include the following:

- Investigate current state of the art SCORPF technology and identify limitations preventing the wide spread use of SCORPF for practical voltage scheduling.
- Develop methods to address some of the most important limitations using available software tools.
- Test and compare these methods to standard established methods on a range of test networks and realistic GB transmission network planning studies.
- Implement these methods into a demonstration tool that is accessible to control centre engineers. Feedback from engineers will need to be obtained in order to iteratively improve the method.

These objectives have been achieved by developing accurate well conditioned optimisable GB transmission network models derived from offline network studies. Similarly optimisation models derived from real-time state estimator snapshots were also built. A highly customised SCORPF procedure, which applies a commercial SCORPF program, was then used to solve the optimisation problem. Various methods were developed that integrate with the program to: improve the objective function reduction, improve the treatment of large discrete shunt devices, improve the multi-objective optimisation reliability, select credible contingency cases and remove contradictory switching solutions. Extensive comparisons were then performed to evaluate the improvement over the standard SCORPF method. Finally a prototype SCORPF demonstration tool was deployed at the GB Electricity National Control Centre.

Contribution to Knowledge

Quantification of the potential of SCORPF for operational loss minimisation

Offline SCORPF models of the GB transmission network have been developed that incorporate approximately 800 credible contingency case events. Previous SCORPF studies reported in the literature have been limited by the fact that the SCORPF problem was only secured against a small number of contingency case events. Solutions obtained by this research to the GB transmission network SCORPF problem have demonstrated that a significant reduction in active transmission losses is possible. A novel three staged SCORPF approach was developed to enhance the SCORPF objective function reduction. On average a 1.9% reduction in transmission losses was achieved using this enhanced approach. This is equivalent to an annualised reduction in carbon dioxide emissions of 64,000 tonnes, the results have also indicated that the voltage stability margin can improve as a result of applying SCORPF. Therefore significant potential for SCORPF technology exists to provide a more standardised and lower loss determination of the reactive dispatch than existing manual methods.

Mixed integer SCORPF method for improved loss reduction

A novel shunt rounding method has been developed to solve the large-scale mixed integer SCORPF problem more effectively than the current state of the art SCORPF technology. Most SCORPF methods have been limited because they handle discrete shunt controls as continuous variables in the main optimisation, these variables are then rounded to their nearest discrete step at the final iteration causing sub-optimality. The current research has addressed this problem by proposing several novel shunt rounding methods. A probabilistic method is described, which fixes a subset of shunts to their nearest discrete value during each iteration of the SCORPF, with a probability determined by a shunts continuous solution proximity to a discrete step. An adaptive threshold method is also described that works in a similar way, but the fixing decision depends on whether or not a shunts continuous solution is within some threshold distance of a discrete step. The current research then presents a detailed comparison of both methods with the standard rounding method. A wide range of networks are compared including the Ward Hale six bus test network, a selection of standard

IEEE networks and a selection of large-scale GB transmission networks with security constraints. A comparison with the MINLP algorithm and KNITRO algorithm, which are based on a branch and bound approach, was carried out on the small-scale networks. The probabilistic method was able to provide near optimal solutions to the mixed integer optimisation problem. An enhanced version of the probabilistic technique was also developed to allow large-scale SCORPF problems with around 800 contingency cases to be solved efficiently. The results from this enhanced technique consistently achieved lower active losses than the standard rounding technique; in addition it sometimes managed to resolve more limit violations.

Constraint-based method for multi-objective optimisation

An SCORPF method has been developed to reduce generator reactive utilisation and transmission losses simultaneously as an alternative to existing multi-objective methods. The standard multi-objective optimisation method that is often applied is to build an objective that consists of linearly weighted functions. One drawback with this technique, which is described in the literature, is that the same weightings applied under different network conditions can result in very different objective function improvements. This phenomenon is observed not only for different power networks, but also for the same network under different conditions. Practically this makes it difficult to decide appropriate weighting values when using a linearly weighted objective function, because of the uncertainty in the final compromise between the objectives. The novel method proposed by this research is based on the principle of applying additional constraints to the reactive flow across generator transformers. This technique is demonstrated on a range of IEEE standard test network models and on a selection of large-scale security constrained GB transmissions network models. The constraint-based technique had more consistent results than the standard weighting technique, for a fixed objective function trade-off parameter across a range of varying network conditions. This consistency has made it the more practical of the two approaches.

Development of a prototype SCORPF control centre tool

A prototype control centre voltage optimisation demonstration tool that delivers secure network plans with lower active transmission losses and generator reactive utilisation has been developed by this project. There are very few examples of practical SCORPF tools deployed in control centres described in the literature. This is likely to be due to the significant challenges involved in developing on-the-fly well conditioned models of the network and determining robust SCORPF solutions. The prototype tool presented in this research, which was made available to engineers at the Electricity National Control Centre (ENCC), demonstrates that it is possible for these tools to be useful in practice. The development of this tool required new SCORPF techniques to be developed in order to handle the accurate and robust optimisation of large-scale network data sets that include a large numbers of contingencies. This tool was evaluated by ENCC engineers who were then able to provide detailed feedback, which was then used to make further improvements to the tool and to provide general recommendations.

Corrective method for contradictory shunt switching

A novel shunt post processing method was developed to improve the final SCORPF solution determined by the prototype control centre voltage optimisation tool. Initially when optimisable shunt capacitor and reactor controls were modelled at different nodes that were electrically close within the model, the SCORPF solution occasionally switched both types of shunt into service simultaneously. ENCC engineers made the observation that this was not a realistic solution that could be implemented in practice. A shunt post-processing logic was then applied to identify problem sites and store the necessary information required by a corrective step. The corrective step then determined the optimal shunt susceptance value required at each problem site, and switched in shunt capacitors or shunt reactors to achieve this susceptance value as closely as possible. This method was able to deliver solutions that consistently had a more realistic shunt switching configuration.

Development of a real-time SCORPF modelling and solution process

A process has been developed that is able to formulate an optimisable model of the GB transmission network from a real-time power network state estimator snapshot, and then perform SCORPF in a robust and reliable manner. Previous literature has stated that the long term aim of SCORPF research should be the development and implementation of a real-time optimisation tool that could run as a contingency constrained closed-loop voltage scheduler. The process developed by this project has been evaluated over a range of network conditions, thereby allowing the potential savings in active transmission losses and generator reactive utilisation to be quantified relative to the original real-time network snapshot. The processes that have been developed have the potential to form an important building block of a future ENCC real-time control centre SCORPF tool.

Publications Arising from the EngD

P. J. Macfie, G. A. Taylor, M. R. Irving, P. Hurlock, H. B. Wan, "Proposed Shunt Rounding Technique for Large-Scale Security Constrained Loss Minimization," *IEEE Transactions on Power Systems*, vol. 25, issue 3, August 2010, pp 1478-1485.

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Chapter 1

Introduction

1.1 Overview

This section provides background information relevant to this thesis. An explanation of transmission losses is included and the ways in which these losses can be reduced at different time horizons is reviewed. The overall objectives of this research are presented within the context of increasing renewable generation connected to the 2020 transmission system [1].

1.2 Operating the GB Electricity Transmission System in 2020

Great Britain's energy sector will face many challenges over the coming years as it adapts to meet stringent climate change targets, which set a requirement for an 80% cut in green house gas emissions by 2050 and a 34% cut by 2020 relative to the 1990 level [2]. Since the power sector is the single largest contributor to UK carbon emissions, responsible for approximately a third of total emissions, significant changes will need to be made to the way in which the power system is operated and controlled. More intermittent generation, such as wind, and larger nuclear power stations will make day to day operations much more complex. The control engineer's job will therefore become more difficult and they will need sophisticated control solutions to help them make key decisions enabling the future transmission network to be operated securely and efficiently. National Grid Control Engineers have a responsibility to perform voltage control switching actions, which affect active transmission losses, reactive generation costs and system security [3]. The number of instructions that the control centre will need to issue to generators is likely to increase dramatically. The transition from the current power system to a 2020 power system will therefore require improved tools and processes to enable the real-time network's voltage profile to be cost effective, secure with lower active transmission losses.



Figure 1-1. National Grid Electricity Control Centre, the voltage switching takes place on the desk directly in front of the transmission network map.

1.3 Environmental Impact of Active Transmission Losses

The transmission of electrical power between generator and demand through a power network results in inevitable active electrical power losses. These losses can be calculated as the difference between power from generators that is going into the transmission system and demand taking power out of the transmission system. Operationally active losses cannot be eliminated, but they can be partially reduced by optimal design and operation of the network. The consumer eventually has to pay for these power losses, which account for around 2% of total generation, and is equivalent annually to the electrical energy consumption of the City of London over a 16 day period [4]. Active transmission losses can be classified into two groups: fixed losses and variable losses. Fixed losses, which are sometimes referred to as iron losses, mainly occur in transformers and other inductive devices connected to the transmission system. Fixed losses arise because the iron core of a transformer is subject to an alternating magnetic field, which dissipates some of this energy in the form of eddy currents and hysteresis loss [5]. Variable losses, which are sometimes referred to as copper losses, account for the majority of the electricity lost on the transmission system. Variable losses occur as a result of the joule heating from the current flows

through resistive elements of the transmission system. The magnitude of the variable losses in a transmission line or cable varies quadratically with the current flow [6].

National Grid has a requirement to estimate the active electrical power losses on the GB transmission network for the year ahead in order to be able to demonstrate operational efficiency, as these losses have an associated financial cost that needs to be met by the users of the network. In 2008/09 the outturn cost of active electrical power losses that occurred on the GB transmission system was £327m based on an energy loss of 5.96TWh valued at £55/MWh [7]. The commercial significance of achieving a reduction in losses is therefore significant, for example consider that optimisation techniques can achieve a 2% reduction in transmission losses. This would be equivalent to an annual energy saving of £6.5m. It is important to note that this would be an economic and environmental benefit to the UK power transmission industry as a whole.

Active transmission losses also have an associated environmental impact. This impact can be determined by considering the generation mix and the marginal environmental impact of each type of generator. Figure 1-2 shows the anticipated changes in the UK's electricity generation mix until 2026. It is important to notice that the fossil fuel based generation still makes up around three quarters of the total generation mix in 2010. By combining this generation mix data with the thermal energy conversion factors shown in Table 1-1 and the plant efficiencies shown in Table 1-2, the approximate environmental impact of active transmission losses due to the burning of fossil fuel can be determined. The annual emissions of carbon dioxide from gas, coal, and oil plant is determined as 2.8 million tonnes per annum. A reduction in active transmission losses would tend to reduce the requirement on the marginal generator, a part-loaded generator that is responding to short-term fluctuations in demand. The flexibility needed for this role, together with typical fuel prices, means that the marginal generator tends to be fossil fuel based. Therefore a reduction in active transmission losses is equivalent to reducing the generation requirement from some fossil fuel based generators.

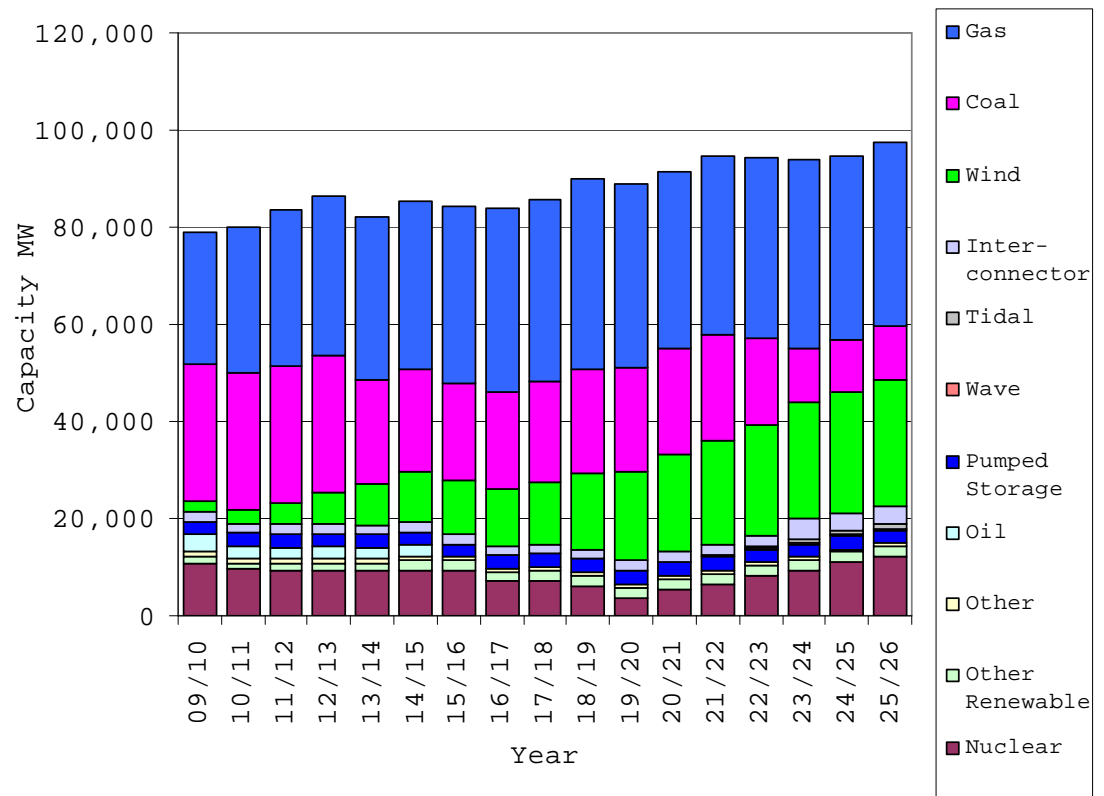


Figure 1-2. Anticipated total UK Generation Capacity from 2009 until 2026 [6].

	CO2
Gas	206
Coal	346
Oil	281

Table 1-1. Thermal energy conversion factors. Units are in grams / kWh [8].

	Efficiency %
CCGT	45
Coal/gas	34
Coal/oil	34
Gas	36
Large Coal	35
Medium Coal	33
OCGT	31
Oil	35
Small Coal	31

Table 1-2. Electrical power plant efficiencies [9].

1.4 Opportunities for GB Transmission Losses Reduction

There are a number of different approaches that could be implemented to reduce active losses on the GB transmission system in planning timescales and operational timescales. The research that will be presented in this thesis is focused on reducing active transmission losses in operational timescales. A variety of loss minimisation methods are therefore reviewed in this section, including methods that can be applied in planning time scales, in order to put the operational reactive optimisation methods into context.

i. Active losses reduction in network expansion planning

Transmission Network Expansion Planning (TNEP) is a basic part of power system planning, which determines where to place new transmission lines and equipment [10]. This problem can be formulated to also consider asset type, so that an appropriate balance can be made for example between low loss equipment and cost. Network power loss is often included as an amortised cost over the expected lifetime of the asset. Typically this kind of planning problem minimizes the network construction and expected operation costs, while meeting the imposed technical and reliability constraints. This type of problem is a complex large-scale combinatorial optimisation problem. To solve this problem National Grid used a tool called SCORPION that is described by Thomas et al. [11] and was used in network planning timescales. These timescales are outside the scope of this project, which focuses on operational tools within timescales ranging from 13 weeks ahead of real-time down to real-time.

ii. Active losses reduction by locating generators close to demand centres

Alternating current (AC) technology has enabled the development of power systems with generators located far away from demand centres. This is because transformers can be used to step up the voltage level, which reduces current flow, and hence reduces network losses. However, for all voltage levels, as the distance between the generator and the demand centre increases the active transmission losses also increases. Therefore building generators closer to the demand centre should generally reduce the transmission losses [12].

iii. Active losses reduction by optimal active power (MW) dispatch

The New Electricity Trading Arrangements (NETA) [13] introduced in 2001 significantly altered the structure of the electricity market in the UK. The new arrangements abolished the centrally regulated pool in favour of a more liberal market based structure, with the majority of generation being self dispatched according to bilateral contractual agreements. This commodity based market does not manage to exactly balance the total demand with the total generation because of fluctuations in demand, generation and losses. In order to achieve the required balance between demand and generation, and obtain a stable system frequency, National Grid has to contract generation at varying timescales to meet the system security and short-term energy balancing requirements. The bilateral power market is frozen at one hour before the 30 minute despatch period, after this time up to real time National Grid can dispatch generation through the balancing mechanism. It is important to note that approximately three percent of the total energy is dispatched through the balancing mechanism. This implies that there is limited flexibility to alter the generation dispatch to reduce transmission losses through the balancing mechanism. Therefore, the focus of the research presented in this thesis has not been on altering the operational active power dispatch.

iv. Active losses reduction by optimal outage scheduling

National Grid's Transmission Requirements (TR) department is responsible for delivery of the system access requirement to the UK electricity network during the current year timescale [13]. This involves accepting and scheduling maintenance and construction work on the transmission system. The manual optimisation team continually update an outage database with information such as re-switching that will be required during a particular week.

Chan, Lau and Ko [14] proposed a genetic algorithm to improve system performance and reduce costs by optimally scheduling outages. This optimised schedule aims to improve system performance reducing financial costs. The conclusion of this research stated that the genetic algorithm managed to provide a capable, simple, and effective method for maintaining outage schedules. It therefore seems reasonable that this technique could be applied to optimally schedule outages when an active transmission losses minimisation objective

function is being applied. Many of National Grid's equipment outage schedules are implemented in studies before operational timescales and these are revised as real time approaches, which is the point in time at which the study is intended to represent. The timing of these outages is often inflexible due to security, demand, and economic reasons. This research has not focussed on determining optimal outage schedules to minimise active transmission losses due to the limited flexibility for alternative solutions.

v. Active losses reduction by optimal reactive power (MVar) dispatch

Chebbo and Irving [15] developed a fully coupled active-reactive dispatch (CARD) algorithm based on a linear programming sparse dual revised simplex method. The purpose of this program was to minimise generator costs and improve other system parameters within defined constraints. Chebbo and Irving considered a number of constraints, in order to ensure security, such as individual circuit flows, generator reactive outputs, power outputs and system voltage. Chebbo, Irving and Dandachi [16] published results from CARD in a second publication. These results were obtained using a 706 bus National Grid network representing a reduced version of the transmission network and considered just one credible contingency case. However, the ability of CARD to scale up to larger realistic power flow optimisation problems was never proven.

Dandachi [17] showed that in principle reactive management on the National Grid transmission system could be improved by utilising a security constrained reactive optimal power flow (SCORPF) that is based on a compact formulation - rather than the sparse formulation approach that was used in CARD. Dandachi recognised the need for the development of a fast mathematically rigorous optimisation tool that could satisfy all security requirements, while maximising dynamic reactive reserves. The tool proposed by Dandachi significantly reduced the time taken to set-up a voltage profile when control centre engineers were starting a new network study, but was limited by the fact that it only considered a small subset of the total number of credible contingency cases. This tool was utilised by Bennett [18] and Bansal et al. [13] to minimise active transmission losses on several pre-BETTA (British Electricity Trading and Transmission Arrangements) network models. BETTA came into force in April 2005 with the

implication that National Grid became System Operator for the Scottish transmission network in addition to the England and Wales networks [13], hence Bennett and Bansal did not include optimisable Scottish transmission network controls in their respective optimisation studies.

The research presented in this thesis builds upon this earlier work by developing and evaluating novel techniques for active transmission losses reduction on a wide variety of post-BETTA networks considering a large number of credible contingencies, Macfie et al. [19, 20]. Significant improvements in the quality and accuracy of the network data have also been made. SCORPF algorithmic techniques have been enhanced to better reflect practical requirements, such as handling discrete devices more effectively [21]. SCORPF therefore provides a viable route forward for this research to minimise reactive costs and active transmission losses.

1.5 Research Objectives

The long-term aim of the general research area is to overcome barriers preventing the wide spread use of practical SCORPF based voltage scheduling tools both in the UK and worldwide. In order to handle the increasing workload associated with operating a transmission system with a large proportion of intermittent generation it is anticipated that more advanced control centre tools will be needed to automate the voltage scheduling process. The research presented in this thesis addresses this need by providing novel techniques that will enable practical SCORPF tools to be implemented in a robust and effective fashion in order to obtain secure cost effective low loss solutions [21, 19, 20, 22, 23].

SCORPF voltage scheduling techniques will need to be proven in the short-term in order to realise a long-term implementation. Therefore the main focus of this research has been on developing techniques to demonstrate the potential for practical secure operational active transmission losses reduction and reactive cost reduction. A prototype SCORPF tool was then made available to control

engineers, so that feedback could be obtained and confidence could be established.

1.6 Contributions to Knowledge

This thesis presents three major contributions to knowledge supported by a selection of minor contributions to knowledge. Most power system optimisation techniques handle discrete shunt controls by treating them as continuous variables in the main optimisation procedure, these variables are then rounded to their nearest discrete step at the final iteration. A number of recent publications have stated that this technique is not adequate, because it degrades optimality and can create infeasible solutions [24, 25, 26, 27]. Existing techniques that are not based on rounding tend to scale inefficiently, because the mixed integer non-deterministic polynomial (NP) problem becomes very difficult to solve [28]. This thesis presents several novel shunt capacitor and shunt reactor discrete switching SCORPF techniques, which are based on a specialised rounding approach. One of the techniques, which was tested on a variety of standard test networks, was able to provide near optimal solutions to the mixed integer optimisation problem. In Macfie et al. [21] the technique is demonstrated on a number of modified IEEE standard networks and on practical large-scale transmission networks. These results are presented in chapter 5 along with the presentation of an enhancement to the technique.

A popular technique that is utilised when performing multi-objective optimisation on power networks is to build an objective that consists of linearly weighted objective functions [29]. One of the drawbacks with this technique, which is described in the literature [30], is that the same weightings applied under different conditions can result in very different objective function improvements. This phenomenon is observed not only for different power networks, but also for the same network under different conditions. Practically this makes it difficult to decide appropriate weighting values when using a linearly weighted objective function, because of the uncertainty in the final compromise between the objectives. This thesis describes an alternative technique for solving the practical

multi-objective problem involving a simultaneous reduction in active transmission losses and reduction in payments to generators for reactive utilisation. The proposed technique is based on the principle of applying additional specially constructed constraints to the reactive flow across generator transformers. In chapter 6 we demonstrate this technique successfully on an IEEE standard test network and on a selection of large-scale security constrained National Grid networks.

A prototype voltage optimisation tool that is secure against a large number of credible AC contingency conditions has also been developed as result of the research presented in this thesis. The prototype tool, which was made available to engineers at the Electricity National Control Centre (ENCC), provides planning recommendations to the ENCC engineers to minimise objectives such as active transmission losses and reactive utilisation costs. The development of this tool has required new techniques to be developed in order to handle the accurate and robust optimisation of large-scale network models that include a large numbers of contingencies. Feedback from ENCC engineers who evaluated the tool is reported in chapter 7 of this thesis.

1.7 Background to the Engineering Doctorate Scheme

The Engineering Doctorate (EngD) is a four year research degree available at Brunel University that has a strong industrial basis [31]. Unlike the traditional PhD, which often has a more theoretical focus, the EngD offers the researcher the chance to design and research practical techniques to solve an existing industry led research problem. The vast majority of the research is carried out within the sponsor's organisation and therefore the researcher gains industrial experience. The research outcomes from an EngD need to be at least the same level as the PhD e.g. the candidate must make a 'contribution to knowledge'. In addition the EngD candidate must follow a program of professional development courses, which are designed to prepare the candidate for an industrial career.

This EngD project was supported by National Grid and the majority of the work was conducted at the ENCC (Electricity National Control Centre) near Wokingham in Berkshire.

1.8 Organisation of Thesis

Chapter 1: Introduction

This section provides background information relevant to this thesis. An explanation of transmission losses is included and the ways in which these losses can be reduced at different time horizons is reviewed. The overall objectives of this research are presented within the context of increasing renewable generation connected to the 2020 transmission system.

Chapter 2: Security Constrained Optimal Reactive Power Flow Overview

This chapter provides the background theory of SCORPF necessary for understand the remaining thesis. Key power system concepts are introduced such as reactive power and voltage control. A generic power system optimisation approach is described, which is followed by a detailed description of the optimisation techniques that underpin the research presented in the remainder of the thesis. These details include general explanation of the Newton-Raphson power flow method, the contingency analysis, the linearisation and the LP solver.

Chapter 3: GB Transmission Technical, Environmental and Commercial Background

This chapter introduces pertinent legal, economic, technical and environmental information relevant the operation of the GB transmission network. Firstly a technical description of active transmission losses is presented. This is followed by descriptive presentations about the metering of active transmission losses, charging for active transmission losses, the balancing services incentive scheme and the reactive market. National Grid's operational practice and existing operational tools relevant to this research are briefly described including an overview of the available operational SCORPF tools. A description of several international SCORPF based voltage control practices is also included with

specific case studies focussed on the Spanish, Belgium and New Brunswick transmission networks. Finally the known SCORPF limitations are summarised, these limitations are categorised into general limitations and limitations specifically with real-time SCORPF.

Chapter 4: Practical SCORPF applied to Large-Scale GB Transmission Network Models

This chapter begins by reviewing relevant security standards that National Grid is required to maintain and then describes the SCORPF formulation and the standard optimisation process. The process of building a detailed and accurate optimisable model of the GB transmission network is explained including the process of remedying modelling errors. A variety of SCORPF results are then presented including sensitivity and boundary flow investigations, which were obtained using the active transmission losses minimisation objective. Finally a multi-stage optimisation technique is introduced, which improves the feasibility and increases the losses reduction of the optimised solution.

Chapter 5: Mixed Integer SCORPF Technique for Loss Reduction

This chapter proposes several novel mixed integer techniques that can be readily incorporated into an existing SCORPF program to solve the optimisation problem more effectively than existing techniques can achieve. The chapter begins with detailed descriptions of several novel shunt rounding techniques, which are demonstrated to produce SCORPF solutions that have lower active losses. The shunt rounding techniques are compared over a range of IEEE standard test network models and large-scale GB transmissions network models. Extensive results are then presented including details of solutions times and the sensitivity to run-time parameters. Finally an enhancement to the shunt rounding technique is described, which is able to solve the full SCORPF problem in a reasonable time on a large-scale GB transmission network models while ensuring that the solution is secure against 800 contingency cases.

Chapter 6: Constraint Based Multi-Objective Optimisation

This chapter describes techniques for modelling and optimising the reactive dispatch problem in a security constrained multi-objective formulation. A novel

technique and a standard technique are compared to address this operational multi-objective problem of determining the appropriate dispatch of reactive controls to reduce active transmission losses and simultaneously reduce generator reactive utilisation. These techniques are investigated using four standard IEEE network models and 26 large-scale practical network models.

Chapter 7: Development and Evaluation of a Prototype SCORPF Control Centre Tool

A prototype SCORPF tool developed by this project has given ENCC engineers direct access to a fully automated optimisation process, allowing them to become engaged and build confidence in reactive power optimisation technology. Firstly, the development and structure of this tool is presented in the chapter. This chapter then shows how feedback was used to develop an updated version of the prototype SCORPF tool to address the requirements of the ENCC engineers that were evaluating it. The updated version of the tool included a novel contradictory shunt switching logic, which was implemented as a solution post-processing step to avoid capacitors and reactors being switched in at the same site. The updated version of the tool also included various extra constraint limits to improve the practical acceptability of the solution. The chapter finishes with a description of how a real-time optimisable SCORPF model was developed from state estimator data. Multi-objective optimisation results derived from these models are presented thereby demonstrating the potential for utilising SCORPF during real-time system operation.

Chapter 8: Conclusions and Future Work

This chapter highlights the main contributions of the research work, to knowledge and to the industry, in the context of the climate change targets and anticipated future operational challenges. Each of these main contributions is then summarised in greater detail and pertinent results and conclusions are described. Finally potential future SCORPF research areas are discussed that would directly build upon the work that is presented in this thesis.

Chapter 2

Security Constrained Optimal Reactive Power Flow

2.1 Introduction

Security Constrained Optimal Reactive Power Flow (SCORPF) techniques offer an important route for improving operational voltage control practices, which still rely on a manual process. The manual process of setting up the target voltage profile can be time consuming and can result in a sub-optimal solution. Therefore it is recognised that the development of a fast mathematically rigorous tool is required [17]. Experience gained over the past forty years has shown that the linear programming (LP) approach can offer a robust and efficient solution over alternative approaches [32]. Alsac et al. [32] demonstrated that a compact LP based SCORPF algorithm could also be used effectively to solve the active losses minimisation problem.

Section 2.1 will introduce the subject of transmission voltage control, which begins with a detailed explanation of the reactive power concept. This section continues with details of the reactive device control modelling used to develop the representation of the National Grid Transmission System in SCORPF problems.

Section 2.3 will introduce established SCORPF techniques that have been developed by Stott and Hobson [33], Stott and Alsac [34] and Alsac et al. [32]. These techniques are exploited in the remaining thesis to solve the large-scale SCORPF voltage control optimisation problem on the National Grid Transmission System. This section begins with a high level overview of the SCORPF method utilised in the thesis. The remaining parts of this section summarise the details of the SCORPF method based on available literature. Where appropriate comparisons with alternative algorithmic methods are presented and discussed.

Finally an explanation of the method used to incorporate contingency case constraints into the optimisation will be provided.

2.2 Reactive Power and Voltage Control

2.2.1 Introduction to reactive power

Reactive power flow on the transmission system is an important concept that needs to be reviewed in order to understand how optimisation can be applied successfully to solve the GB voltage optimisation problem.

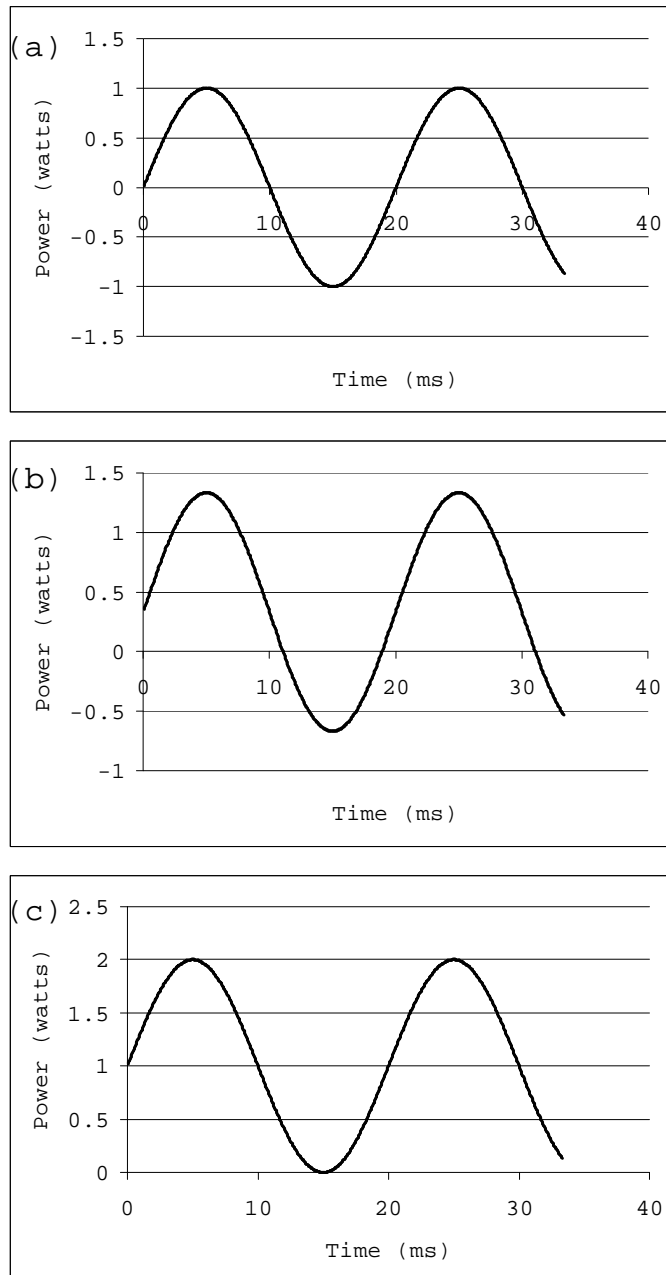


Figure 2-1. Instantaneous electrical power flow versus time flowing across a point on a network under different reactive power flow conditions. (a) only real power flow, (b) mixture of real and reactive power flow, (c) only reactive power flow.

Electrical power flow is the rate of flow of energy transmitted across a given point on a network. In alternating current (AC) circuits energy is stored temporally in inductive and capacitive elements, which results in the periodic reversal of the direction of power flow. The portion of power flow remaining after being averaged over one complete AC waveform is the real power, which can be used to do work, for example to overcome friction in a motor, or heat an element. Conversely the portion of energy that is temporally stored on the network in the form of an electric or magnetic field, due to inductive and capacitive network elements is known as the reactive power. Reactive power flows are required to support the transfer of real power over a network. A better understanding of the physical nature of reactive power can be gained by considering the instantaneous power flow across a point on a network, which is given by the product of voltage and current at an instant in time. Figure 2-1 illustrates the instantaneous power flow versus time flowing across a point on a network under three reactive power flow conditions. The concept presented by box (a) is that only real power flow exists. In box (c) only reactive power flow exists, such that the portion of power flow remaining after being averaged over a complete AC waveform is zero. This means that no real power is transferred, as all energy is temporarily stored in the form of electric or magnetic fields before being returned to the source. In box (b) there is a mixture of real and reactive power flow. The conceptual understanding of reactive power can be further enhanced by considering the phase angle between the voltage and current in the three different scenarios. In box (a) the current is in phase with the voltage, which means that only real power is transmitted, because the instantaneous power can never flow in the reverse direction. In box (c) the current is 90 degrees out of phase with the voltage and therefore only reactive power is transmitted [35].

2.2.2 Voltage control device models

The following sections review the voltage control modelling of the GB Electricity Transmission Network [36]. Consider Ohms Law for a transmission line with impedance Z , a current of I , sending end voltage V_s and receiving end voltage V_r :

$$V_s - IZ = V_r \quad (2-1)$$

V_r is the voltage that is being regulated by the control device. Two methods of controlling the receiving end voltage can be determined from equation 2-1.

- 1) Increase or decrease the sending end voltage to increase or decrease the receiving end voltage
- 2) Increase or decrease the voltage drop across the transmission line to decrease or increase the receiving end voltage, this can be done by adjusting the current flow. This method is known as Power Factor Correction.

2.2.3 Generator excitation control modelling

The excitation circuits in generators can be used to regulate voltage at the sending end [35]. Generators are connected to the National Grid transmission network by a transformer, as shown in Figure 2-2. The primary winding is at the low voltage side of the transformer and is connected to the generator terminal. The secondary winding is at the high voltage side of the transformer and is transmission connected. The tap changer is always on the high voltage side of the transformers due to the extremely high currents that flow on the LV side.

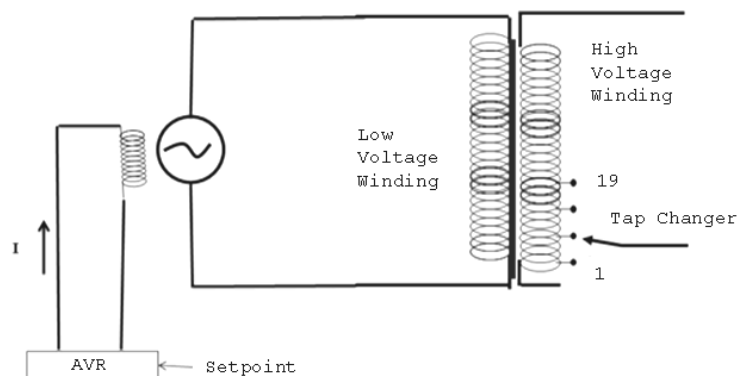


Figure 2-2. Generator with an automatic voltage regulator (AVR) connected to the transmission network by a two winding transformer.

To increase the HV voltage the tap changer must be lowered from the top tap 19 to the bottom tap 1. Initially when the tap is lowered there is limited change in the voltage on the HV side, because the HV side acts as an almost infinite bus bar. The voltage on the LV side will however fall. The fall in the LV side voltage is detected by the generator's automatic voltage regulator (AVR), which responds by increasing the rotor field current which has the effect of increasing the voltage

at the generator terminals. The lagging reactive power output from the generator is therefore increased, which will lead to an increase in the HV side voltage. To lower the HV voltage the tap is raised and the above process works in reverse, such that the lagging reactive power output from the generator is reduced.

Most generator AVR schemes on the GB transmission network maintain the voltage at the LV bus at a fixed target of 1pu. The AVR utilises a proportional, integral, derivative closed loop control system to maintain this voltage target.

The generator transformer is often modelled as voltage regulating for the intact network case, which means that the tapping is automatic to maintain the HV voltage target. The HV voltage is regulated by the transformer, while the LV voltage continues to be regulated by the generator's AVR scheme. In practice generator transformers do not perform automatic tapping. Instead the generator transformer tap is raised or lowered in response to reactive power flow target instructions manually issued from the ENCC. It is considered acceptable to model generator transformers with automatic tapping under steady state conditions because there is time for all instructions to be issued. Under contingency conditions generator transformers are modelled as fixed tap to reflect the fact that there is no automatic tapping and not enough time to manually issue instructions to change the reactive power target.

2.2.4 Transformer modelling

Transformers can be used to adjust the voltage difference between the sending and receiving ends of a transmission line [37]. Consider a transformer that consists of two windings, primary and secondary that are wound on a magnetic former. The secondary winding will have various connections, and a tap changer, as shown in Figure 2-3. The relationship between the voltage, current and number of turns is given in the following equations. V_1 and N_1 are normally fixed, N_2 can be varied to modify the voltage V_2 .

$$\begin{aligned} V_1 N_2 &= V_2 N_1 \\ I_1 N_1 &= I_2 N_2 \end{aligned} \tag{2-2}$$

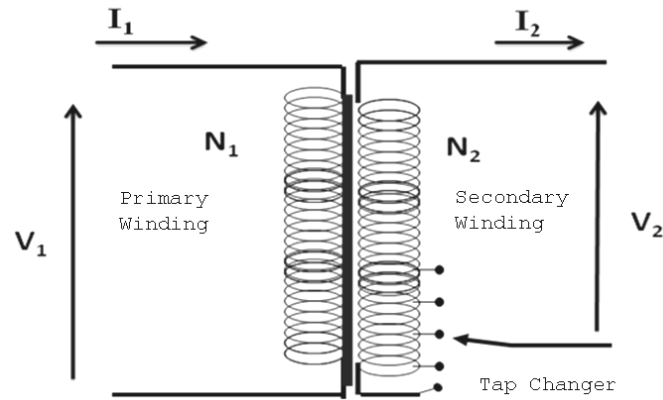


Figure 2-3. Transformer tap changer

2.2.5 Shunt capacitor and shunt reactor modelling

Shunt capacitors and shunt reactors are modelled as providing a discrete quantity of reactive power at a voltage of one per unit. When the voltage changes the quantity of reactive power generated or absorbed will be different. Shunt compensation equipment can be installed onto the network anywhere that may require additional voltage support and can be switched into and out of service as required, with the reactive power injection from a shunt connected device equal to BV^2 [35]. The switching in of a shunt capacitor will therefore become less effective as the voltage drops at a location on the network. This can pose a problem for ENCC engineers who need to switch in a shunt capacitor to recover a sagging voltage. Reactive power control is therefore extremely important in the maintenance of a satisfactory system wide voltage profile.

Shunt Capacitor

A phasor representation is given in Figure 2-4 showing the effect of transmission line impedance on the receiving end voltage relative to sending end voltage. The receiving end voltage is lower than the sending end voltage because of this impedance. Figure 2-4 also shows the effect of injecting a capacitive current I_c , which combines with I to give a current of I' at the receiving end. The voltage drop is then reduced from IZ to $I'Z$. Notice that after switching in the capacitor the angle between I and V_s reduces, which corresponds to a power factor closer to unity. This technique is known as power factor correction.

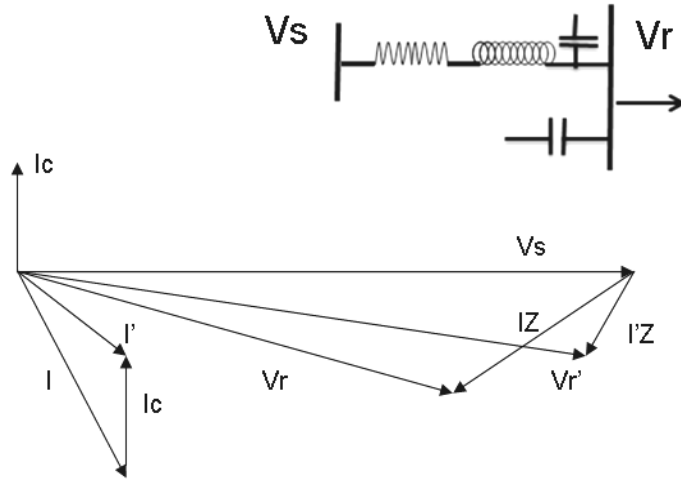


Figure 2-4. Capacitive VAR Injection

Shunt Reactor

The effect of inductive VAR injection can be understood by considering the reverse of the situation illustrated in Figure 2-4. The inductive current is injected from the shunt reactor and has the effect of reducing the receiving end voltage. This is useful when the voltage needs to be suppressed, such as during the night when the demand is low.

2.2.6 Static VAR compensator (SVC) modelling

Thyristor controlled Static VAR Compensators (SVCs) were developed in the 1970s to act as compensation for arc furnaces, these devices are one of the earliest types of Flexible AC Transmission System (FACTS) controllers [36]. The typical shunt connected SVC consists of thyristor controlled reactors and thyristor switched capacitors. The full continuous range of the SVC can be accessed by coordinating the switching of the discrete capacitor block and the continuous reactor controls. Figure 2-5 is a diagrammatic representation of a typical SVC connected to the GB transmission network.

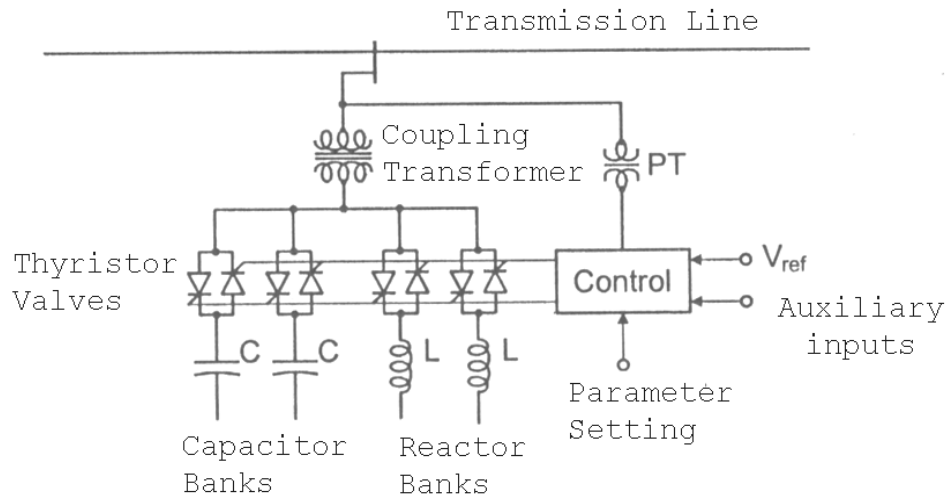


Figure 2-5. SVC with thyristor switched capacitors and thyristor controlled reactors. [36]

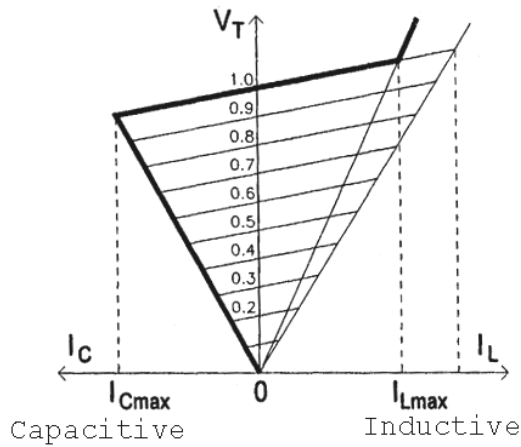


Figure 2-6. V-I characteristic of an SVC. [36]

The SVC is usually operated in a voltage regulating mode, which adjusts its susceptance to maintain the local transmission network voltage to a voltage set-point value. The SVC can also operate in a constant MVar mode, which maintains a fixed value of susceptance under steady state conditions. The V-I characteristic of an SVC operating in voltage regulating mode is shown in Figure 2-6, which indicates that the voltage is maintained to within a band around the voltage set point until the maximum inductive current or maximum capacitive current is reached. The control slope is intended, so that the voltage support duty is shared between SVCs and generators at different points in the network [38]. A slope of 4% is usually applied to give approximately the same response as a generator. The slope provides many merits such as prevention of banging between reactive power limits, load sharing between voltage regulation devices and

reduction of the SVC rating. Figure 2-6 shows that outside the operating range, the SVC becomes a fixed capacitor or a fixed reactor.

National Grid operates several SVCs in constant MVar mode during normal operation. However under contingency conditions these SVCs switch back to voltage regulation mode in order to ensure system security and stability.

2.3 Security Constrained Optimal Reactive Power Flow

2.3.1 General approach

This section describes a high level overview of the workings of the SCORPF algorithm that is utilised by this research. Sections 2.3.2 to 2.3.9 provide details and references corresponding to each stage of the SCORPF method described in this section.

SCOPE, a commercial optimisation program produced by Nexant in the USA, has been utilised to perform the calculations presented in this thesis [39]. SCOPE was chosen because the program includes a powerful, mature and robust SCORPF algorithm that has been developed over the last 30 years. The SCORPF algorithm is based on a compact primal dual LP solver. A large number of credible contingency cases are considered within the SCORPF to ensure that the final solution is secure for a large number of user defined contingency cases. Each contingency case is derived from the intact network with one or more network components flagged as outaged.

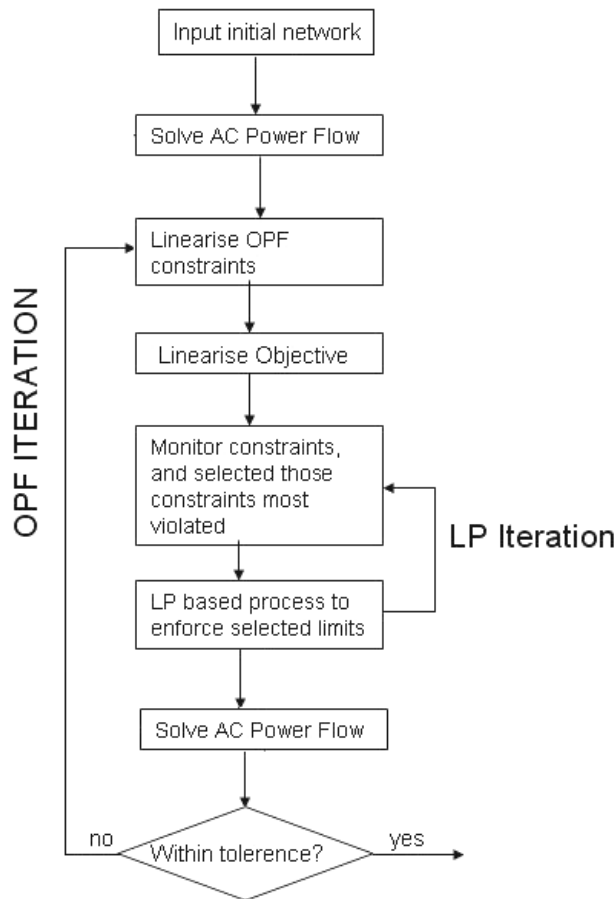


Figure 2-7. SLP based SCORPF processes. Modified from Alsaç et al. [32].

Figure 2-7 shows a flow diagram indicating the steps of the main SCORPF approach utilised in this thesis. Initially a power flow solution is obtained for the intact network and each contingency case using a suitable power flow algorithm such as the Newton Raphson Power Flow or Decoupled Power Flow, which will be described in sections 2.3.2 to 2.3.4. The power flow is deemed to have been solved when all bus mismatches are within the required tolerance and all local controls are satisfied [32].

The SCORPF method needs to start from a converged power flow solution in both the intact network case and in contingency cases. The independent control variable limits within the optimisation should always be initially satisfied, but some dependent variables may be violated. Violations are monitored at each stage of the optimisation and the most violated constraints are enforced within the LP process, which is based on a Simplex method [40].

The power flow equations and objective are linearised using the method explained in section 2.3.7. The LP method described in section 2.3.8 forms a sub-problem that needs to be solved within the overall SCORPF method shown in Figure 2-7. The solution from the LP method will ensure that all hard constraints have been satisfied, but there is no requirement to satisfy any convergence tolerances. The solution from the LP method is a set of intact network control updates [32].

The updated control variables are then inserted into the AC power flow equations, which are re-solved using the selected power flow method. The solution is obtained when the changes to the control variables are less than the defined tolerance, the power flow equations are satisfied and all hard constraints are satisfied. If at least one of these criteria has not been satisfied then the power flow and objectives are re-linearised at the new operating point and the process is repeated. If the solution to the SCORPF problem appears infeasible then each constraint causing a bottleneck is allowed to become soft. This means that the constraint is allowed to violate its limit and a penalty function is added to the objective function with a magnitude dependent on the amount of violation [32].

Including contingency constraints is fundamental to achieving a secure optimisation solution. The contingency case list considered by the optimisation within this research was large typically around 800 cases. Therefore the total number of individual constraints considered in a SCORPF can reach millions because each case can include thousands of extra constraints. In practice it has been noted that very few of these constraints become binding during the solution process, which is a feature that makes SCORPF a feasible solution technique.

Full contingency analysis must be performed before starting the main SCORPF method and a partial contingency analysis is also performed for a select number of cases at each SCORPF iteration of Figure 2-7 [34]. Contingency cases that have a violation or are close to having a violation are stored in a critical contingency list that is updated periodically. This list is regularly updated by adding or removing critical contingency cases based on the results from a full contingency power flow across all cases - for example the list could be updated at every tenth iteration of the main SCORPF. By selecting a small subset of binding contingency case

constraints from all contingency case constraints the execution time of the overall SCORPF is reduced substantially. This is because the size of the LP optimisation problem that needs to be solved at each iteration is substantially reduced compared to any approach that includes constraints that are not being violated.

2.3.2 Power flow

The power flow solution process involves calculating the values of dependent variables on a power system, which is being operated under balanced three-phase steady-state conditions. Once these quantities have been determined real and reactive power flows, as well as active losses, can be computed. Solving the power flow problem will be critical in analysing, understanding, and optimising National Grid's transmission network.

A one-line diagram is commonly used to represent a balanced three phase power system, as it simplifies the illustration of the system while preserving necessary information for network analysis [41]. These diagrams generally include the generators, transformers, loads and other three phase equipment that make up the network. This equipment is connected to busbars, which act as nodes in the calculation, and these busbars are connected to one another by transmission lines. The input data to the power flow problem will typically include transmission line data, bus data and transformer data. The per-unit system is used to represent the impedances, voltages, currents, real power flows and reactive power flows when solving power flow problems [37].

Each bus (k) on the network has four variable associated with it:

- Voltage magnitude V_k
- Phase angle δ_k
- Net real power P_k supplied to the bus. $P_k = P_{Gk} - P_{Dk}$ (G =generator, D =demand)
- Net reactive power supplied to the bus. $Q_k = Q_{Gk} - Q_{Lk}$

Each bus on the network can be categorised into one of three types depending on the variables that are known [37]:

- Slack bus. The slack bus can be defined as a single bus or a distribution of busbars. Consider the case of a single slack bus that will take up the ‘slack’ if the generated real and reactive power does not balance the real and reactive power that is absorbed by the load and power losses of the network. The V_k and δ_k are the known parameter, so the power flow algorithm calculates the values of P_k and Q_k . By convention the slack bus is usually defined to have a voltage angle of zero. The slack bus is usually labelled as bus one and can also act as a reference bus for the entire network. [42].
- Load bus (PQ bus). Constants P_k and Q_k are specified in the input data. The power flow algorithm will compute V_k and δ_k .
- Voltage controlled bus (PV bus). Constants P_k and V_k are specified in the input data. The power flow algorithm will determine Q_k and δ_k . Generators, shunt capacitors, and static VAR systems can be connected to this bus. Limits on reactive power generation can be specified in the input data. If a reactive power limit become binding during the power flow solution process then the bus will revert to a PQ bus.

In order to perform power flow the bus admittance matrix Y_{bus} must be specified. Each element of Y_{bus} has the form $G + jB$, conductance plus imaginary susceptance. This matrix represents the transmission line and transformer data. The matrix can be built up using the following scheme [37]:

Diagonal elements: $Y_{kk} = \text{sum of all admittances connected at bus } k$.

Off diagonal elements: $Y_{ki} = -(\text{sum of admittances connected between busbars } k \text{ and } i)$

For each row of the admittance matrix at most only four elements are typically non zero. The sparsity of this matrix is important for efficient storage and computation when solving the power flow problem [33].

The non-linear power flow equations are at the heart of the power flow computation. These equations describe the real and reactive power supplied at each bus. The power flow computation attempts to solve these equations typically

using an iterative procedure. To obtain the power flow equations we must start from the equation that describes the complex power injected at a node [43].

$$S_k = P_k + jQ_k = V_k I_k^* \quad (2-3)$$

Where S_k is the complex power injected at node k .

P_k is the active power injection

Q_k is the reactive power injection

V_k is the complex voltage

I_k is the complex current injection

The injected current I_k is given by the following expression. Where Y_{ki} is the admittance of the branch k to i .

$$I_k = \sum_{i=1}^N Y_{ki} V_i \quad (2-4)$$

Substituting equation 2-4 into equation 2-3 gives the following:

$$P_k + jQ_k = V_k \sum_{i=1}^N Y_{ki}^* V_i^* \quad (2-5)$$

The polar form of the voltages is given below.

$$V_k = |V_k| e^{j\delta_k} \quad V_i = |V_i| e^{j\delta_i}$$

Substituting these into equation 2-5 and expanding gives the following expression for power flow:

$$P_k + jQ_k = |V_k| \sum_{i=1}^N |V_i| (G_{ki} - jB_{ki}) e^{j(\delta_k - \delta_i)}$$

Expand the complex exponential term:

$$P_k + jQ_k = |V_k| \sum_{i=1}^N |V_i| (G_{ki} - jB_{ki}) (\cos(\delta_k - \delta_i) + j \sin(\delta_k - \delta_i))$$

Finally separate the real and imaginary components corresponding to the active and reactive power flows at each node:

$$P_k = |V_k| \sum_{i=1}^N |V_i| (G_{ki} \cos(\delta_k - \delta_i) + B_{ki} \sin(\delta_k - \delta_i)) \quad (2-6)$$

$$Q_k = |V_k| \sum_{i=1}^N |V_i| (G_{ki} \sin(\delta_k - \delta_i) - B_{ki} \cos(\delta_k - \delta_i))$$

V_k and V_i are the nodal voltage magnitudes at nodes k and i respectively. δ_k and δ_i are the nodal voltage phase angles at nodes k and i . These equations are non-linear and the solution is reached iteratively.

2.3.3 Newton-Raphson power flow

The most popular procedures used to solve the above equations are based on Newton-Raphson or Gauss Seidel algorithms [41]. The Newton-Raphson algorithm will be briefly explored here, as it features faster quadratic convergence. Solving the power flow equations can be likened to solving for X in $Y=f(X)$. This can be solved for X by iteratively evaluating the following, where m is the iteration number:

$$X(m+1) = X(m) + \mathbf{J}^{-1}(m)(Y - f(X(m))) \quad (2-7)$$

\mathbf{J} is known as the Jacobian and each element is given by $\mathbf{J}(m) = \left(\frac{df(X)}{dX} \right)_{X=X(m)}$

The vectors X , Y and $f(X)$ are explicitly shown below for each bus. The voltage and angle at the slack bus is already known, and therefore the slack bus is not included in the following vectors:

$$X = \begin{bmatrix} \delta_2 \\ \dots \\ \delta_N \\ V_2 \\ \dots \\ V_N \end{bmatrix} \quad \text{Angles and voltages that need to be solved.}$$

$$Y = \begin{bmatrix} P_2 \\ \dots \\ P_N \\ Q_2 \\ \dots \\ Q_N \end{bmatrix} \quad \text{Real and reactive powers at each bus.}$$

$$f(X) = \begin{bmatrix} P_2(x) \\ \dots \\ P_N(x) \\ Q_2(x) \\ \dots \\ Q_N(x) \end{bmatrix} \quad \text{Calculated real and reactive powers.}$$

Equation 2-7 is solved for each bus multiple times during the power flow computation. At each iteration a Jacobian matrix needs to be formed, and is composed of partial derivatives from the power flow equations. The Jacobian matrix is formed from four blocks.

$$\mathbf{J} = \begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \dots & \frac{\partial P_2}{\partial \delta_N} & \frac{\partial P_2}{\partial V_2} & \dots & \frac{\partial P_2}{\partial V_N} \\ \dots & & \dots & \dots & & \dots \\ \frac{\partial P_N}{\partial \delta_2} & \dots & \frac{\partial P_N}{\partial \delta_N} & \frac{\partial P_N}{\partial V_2} & \dots & \frac{\partial P_N}{\partial V_N} \\ \frac{\partial Q_2}{\partial \delta_2} & \dots & \frac{\partial Q_2}{\partial \delta_N} & \frac{\partial Q_2}{\partial V_2} & \dots & \frac{\partial Q_2}{\partial V_N} \\ \dots & & \dots & \dots & & \dots \\ \frac{\partial Q_N}{\partial \delta_2} & \dots & \frac{\partial Q_N}{\partial \delta_N} & \frac{\partial Q_N}{\partial V_2} & \dots & \frac{\partial Q_N}{\partial V_N} \end{bmatrix} \quad (2-8)$$

The Newton-Raphson procedure is iterative. Initially the $x(m=0)$ vector is populated with values of $\delta=0^\circ$ and $V=1.0pu$, at each iteration this vector is updated. The following steps are performed at each iteration:

- Computation of the mismatch vector, which is a vector of the differences between the known powers injected at each bus and the powers

determined from the power flow equation. The mismatch is therefore the value of $Y-f(X)$ in equation 2-7.

- The Jacobian matrix is calculated using equation 2-8.
- This Jacobian matrix is then inverted and multiplied by the mismatch vector to find the ΔX values.
- Finally new X values are computed using $X(m+1) = X(m) + \Delta X(m)$.

This procedure is repeated until convergence of the power mismatch vector is obtained or the maximum number of allowed iterations is reached. Newton Raphson normally requires only four or five iterations to converge. The whole process is illustrated diagrammatically in Figure 2-8.

The bus voltages and angles contained in the X vector describe the state of the system once power flow convergence has been achieved. One can then apply equation 2-6 to determine the real and reactive power flows injected at each bus, the branch power flows and the total active losses.

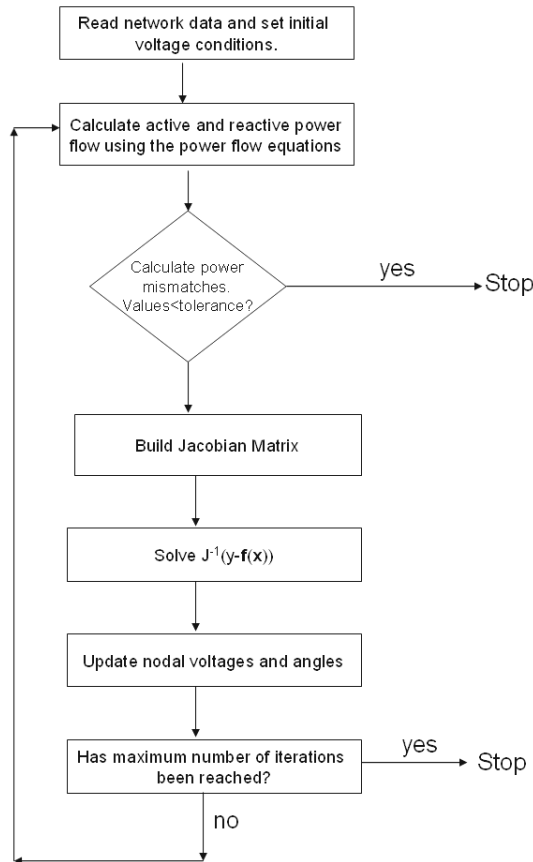


Figure 2-8. Flow diagram of the Newton-Raphson algorithm. [41]

2.3.4 Decoupled power flow

The Newton Raphson power flow algorithm is a robust power flow algorithm, however the Jacobian matrix must be recalculated at every iteration. When a large number of power flow problems need to be solved then it is useful to make simplifications in order to reduce convergence time [44].

- It can be shown that real power transfer has a low sensitivity to voltage magnitude and therefore we can neglect the interaction between P_k and V_i such that the components in the upper right quartile of the Jacobian become zero.
- Similarly the reactive power has a low sensitivity to power angle and therefore we can neglect the interaction between Q_k and δ_i such that the components in the lower left quartile of the Jacobian become zero.

The resulting Jacobian then has the form:

$$\mathbf{J} = \begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \dots & \frac{\partial P_2}{\partial \delta_N} & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \frac{\partial P_N}{\partial \delta_2} & \dots & \frac{\partial P_N}{\partial \delta_N} & 0 & \dots & 0 \\ 0 & \dots & 0 & \frac{\partial Q_2}{\partial V_2} & \dots & \frac{\partial Q_2}{\partial V_N} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & 0 & \frac{\partial Q_N}{\partial V_2} & \dots & \frac{\partial Q_N}{\partial V_N} \end{bmatrix} \quad (2-9)$$

Updates to δ_m and V_m are given by the following iterates:

$$\delta(m+1) = \delta(m) + \left[\frac{\partial P}{\partial \delta} \right]^{-1} \Delta P \quad (2-10)$$

$$V(m+1) = V(m) + \left[\frac{\partial Q}{\partial V} \right]^{-1} \Delta Q \quad (2-11)$$

Equation 2-10 and Equation 2-11 can be solved iteratively. The main advantage of decoupled power flow over Newton Raphson power flow is that the computer time spent factorising matrices is significantly reduced. This reduction in computing time is important when solving a large number of contingency power flow problems.

2.3.5 SCORPF generalised problem

The operational SCORPF problem can be formulated as the general mathematical problem of finding the near to real-time optimal operational plan for a power system[45,46], while meeting operational feasibility and security requirements. The SCORPF general formulation can be stated as [47, 48]:

$$\text{Minimise } f(U^0, X^0) \quad (2-12)$$

U is a vector of the control variables and X is a vector of dependent variables. The superscript 0 indicates that the variable refers to the pre-contingency power system.

The SCORPF is bound by equality and inequality constraints. The equality constraints are given by the pre and post contingency power flow equations, where superscript c refers to the c 'th contingency case:

$$g^c(U^c, X^c) = 0 \quad c=0, 1 \dots n \quad (2-13)$$

The equipment and operating limits are given by the following inequalities. Hard constraints on controls are represented by:

$$U_{MIN}^c \leq U^c \leq U_{MAX}^c \quad c=0, 1 \dots n \quad (2-14)$$

Inequality constraints on variables are represented by:

$$h^c(U^c, X^c) \leq 0 \quad c=0, 1 \dots n \quad (2-15)$$

2.3.6 Attributes classifying power system SCORPF problems

SCORPF methods can be characterised by five attributes [49].

- Modelling. This refers to the physical problem. This includes modelling the data and the way in which state variables are determined.
- Formulation. This is the presentation of the mathematical model to the optimisation algorithm.
- Algorithm. This is the mathematical optimisation solver, which solves the mathematic model presented by the formulation stage.
- Constraint Handling. The algorithm needs a method for handling constraints that become binding.
- Implementation. This focuses on the software aspects of the overall implementation.

2.3.6.1 SCORPF system modelling

Accurate network modelling is crucial for achieving reliable optimisation results. This is perhaps the single most demanding area that needs to be addressed in order to be able to obtain meaningful SCORPF solutions to the GB transmission network voltage optimisation problem.

The system model modelling needs to consider the following data issues [19]:

- Accuracy of topology and line/transformer impedances.
- Intact network case and contingency models.
- Controls. Need to consider limits and if the control is continuous or discrete.
- Constraint limits. Choice of hard or soft penalties limits. Different constraint limit sets need to be specified for base and contingency cases.
- Transformer tap ranges need to be accurate. Also need to consider if transformer is acting as a local voltage control.
- Area and zone controls and constraints.
- Cost models. For example reactive power payments to generators need to be modelled at the commercial boundary.
- Dynamic reactive reserve needs to be applied to generators and SVCs.

In addition, the choice of algorithm used to determine the dependent variables in the power flow needs to be considered. The main algorithms that are used in this

thesis are the Newton Raphson Power Flow and Decoupled Power Flow algorithms, which were introduced in sections 2.3.3 and 2.3.4.

2.3.6.2 SCORPF formulation

The optimisation problem can be modelled as composed or decomposed [49]. The composed formulation considers the entire problem in one complete mathematical formulation, which contains all controls and constraints. The generalised composed SCORPF problem was shown mathematically in section 2.3.5.

The decomposed formulation breaks down the problem into multiple sub-problems. These are solved separately and integrated iteratively. A common decomposition method is to formulate the optimisation problem separately in terms of U and X variables, which were defined in section 2.3.5. The decomposed problem has reduced dimensionality and can usually be solved more quickly. Ill conditioning can sometimes occur when decomposing the optimisation problem, which tends to lead to reduced robustness.

2.3.6.3 OPF algorithm

The techniques described in this section have been used to solve OPF problems and are relatively mature [43, 49, 50, 51]. They all require that the network optimisation problem is appropriately modelled and formulated. This section presents a comparison of the popular mathematical techniques that can also be used to solve the full SCORPF problem.

Linear programming (LP) techniques – The nonlinear OPF problem needs to be linearised in order to convert it to a linear optimisation problem [48]. LP based techniques are fast and reliable. These features make LP suitable for applications where reliability and speed are important. The Successive Linear Programming technique determines an approximate solution by linearising the full OPF problem, which is then solved to determine an update to the operating point using a predictor – corrector approach [52]. A more detailed explanation of the LP based approach adopted in this thesis is described in section 2.3.8.

Interior point method – Karmarkar [53] proposed a method for solving large-scale power system optimisation problems, which can solve these problems in polynomial time. The solution is based on a series of projective transformations and optimisations, which create a series of points that should converge on the optimum. The method is called interior point because of the path through the feasible region during the solution process. An important feature of the interior point method is that the number of iterations is not dependent on problem size.

Gradient techniques – The principle of the gradient technique is to express the gradient of the objective function as a function of independent variables [54]. A progression direction is then defined based on this gradient. The optimum is reached when the gradient of the objective function has been reduced to zero.

Quadratic Programming (QP) techniques – The successive QP technique works in a similar way to LP using a predictor-corrector approach. The optimisation problem, which could be highly non-linear and non-quadratic, is approximated using quadratic functions. The current operating point is updated and the predictor-corrector approach is iterated until convergence is achieved [49].

2.3.6.4 Constraint handling

Three techniques are briefly described for constraint handling within the OPF techniques described above. The simplest approach for handling constraints is to convert violated inequality constraints to an equality constraint. If the inequality is no longer violated then the constraint should be freed from its limit.

The Lagrange Multiplier Method [49]. – The constrained minimisation problem is converted to the problem of finding the minimum of the unconstrained Lagrange function given below:

$$L(U, X, \lambda) = f(U, X) - \lambda \cdot g(U, X) - \lambda' \cdot h(U, X) \quad (2-16)$$

$g(U, X)$ represents the binding equality constraints and $h(U, X)$ represents the binding inequality constraints. λ and λ' represent the Lagrange multipliers

associated with the equality and inequality constraints respectively. Finding the solution of equation 2-16 therefore represents an unconstrained optimisation problem.

Penalty Function Method [55] – This method also converts the constrained minimisation problem to an unconstrained minimisation of the augment function:

$$f(U, X) = f(U, X) + \sum w_j a_j(U, X)^2 \quad (2-17)$$

w_j are the weightings on the penalty function, a_j is a function representing the violation of each binding constraint, and j is the number of the binding constraint.

Simplex-Based Methods [40] – These methods are utilised in LP, QP and gradient techniques. A tableau, which contains the coefficients of the linearised equality and inequality constraints, is maintained. There are different versions of the Simplex method, but in general they operate in the following way. At any stage during the optimisation process variables can be fixed on limits (basic) or they are floating (non-basic), the solution to the non-basic variables is determined by solving a basis matrix. This matrix contains the current active constraints in the tableau and is updated at each iteration. When the optimisation process needs to enforce a new limit, the relevant inequality is converted to an equality constraint. This means that the constraint becomes active and its coefficient enters the basis matrix in exchange for a previously enforced constraint that is freed.

2.3.6.5 Implementation

The practical implementation of an OPF control centre tool will need to deal with the issue of execution efficiency and user interface. A selection of implementation issues are described in this section some of which will be returned to in chapter 7 [49]. Many concepts relevant to the OPF are illustrated in Figure 2-9; the most important concepts relating to this research have been underlined.

Sparsity/compact: Sparsity plays a major role in the efficiency of power system analysis tools. OPF methods can benefit from applying techniques that make use of sparsity in formulation and algorithmic stages. There have been two streams of

development of OPF tools. One which maintains sparsity in the formulation of constraints, Chebbo and Irving [15], and another that applies a compact formulation of constraints, Stott and Hobson [33]. Practical experience would suggest that the compact formulation normally results in a more efficient solution process because only a relatively small percentage of the constraints become binding during the solution process. This means that the benefit associated with utilising sparsity does not exceed the benefit of ignoring the vast majority of constraints.

Piece-wise/Singe-shot: To improve the accuracy of the OPF final solution the problem can be solved using successive approximations updated iteratively during the solution process. An alternative to this is to solve the OPF problem in a single stage, which is only viable if the problem formulation is accurate [49].

Usability: Most commercial and third party OPF packages available today suffer from weak user and data interfaces. These factors have limited the use and application of OPF methods in practice within the industry. This is an area that will need to be addressed in order to realise practical tools that are useful to planning and control engineers [49].

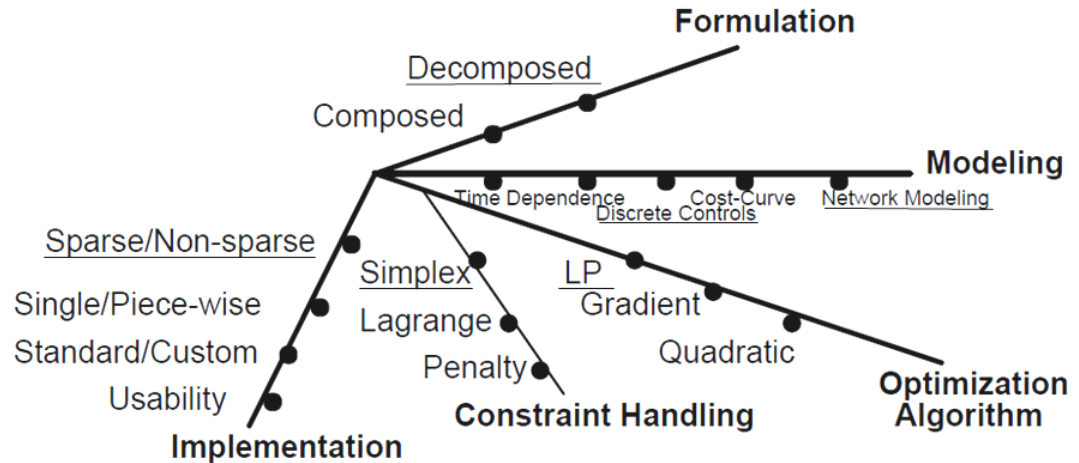


Figure 2-9. Classification of OPF concepts, the important concepts for this research have been underlined. Adapted from [49].

2.3.7 Linearised modelling

The nodal power flow equations were given in equation 2-6. These equations can be reformulated as branch power flow equations [56] that represent the flow

between the ends of each branch with series admittance $G + jB$, and shunt susceptance $G_i^{sh} + jB_i^{sh}$ and $G_k^{sh} + jB_k^{sh}$ at each end of the branch. The transformer tap has ratio a , phase shifter angle P and refers to the i side of the transformer. When $a=1$ and $P=0$ the equations represent the power flow across a transmission line.

$$\begin{aligned}
P_{ik} &= -a.V_i.V_k.(G.\cos\theta + B.\sin\theta) + G_i.a^2.V_i^2 \\
Q_{ik} &= -a.V_i.V_k.(G.\sin\theta - B.\cos\theta) - B_i.a^2.V_i^2 \\
P_{ki} &= -a.V_i.V_k.(G.\cos\theta - B.\sin\theta) + G_k.V_k^2 \\
Q_{ki} &= a.V_i.V_k.(G.\sin\theta + B.\cos\theta) - B_k.V_k^2
\end{aligned} \tag{2-18}$$

where

$$\theta = \delta_i - \delta_k + P \quad (\theta \text{ is the phase angle difference between the ends of the branch})$$

$$G_i + jB_i = G + G_i^{sh} + j(B + B_i^{sh})$$

$$G_k + jB_k = G + G_k^{sh} + j(B + B_k^{sh})$$

The linearised constraints that are applied within the optimisation are based upon the following linearised version of the power flow equations. These are:

$$\begin{aligned}
\Delta P_{ik} &= (G.\sin\theta - B.\cos\theta).(\Delta\delta_i - \Delta\delta_k + \Delta P) - (G.\cos\theta + B.\sin\theta).(\Delta V_i/V_i + \Delta a/a + \Delta V_k/V_k) \\
&+ 2G_i.a^2.V_i^2(\Delta V_i/V_i + \Delta a/a)
\end{aligned}$$

$$\begin{aligned}
\Delta Q_{ik} &= -(G.\cos\theta + B.\sin\theta).(\Delta\delta_i - \Delta\delta_k + \Delta P) - (G.\sin\theta + B.\cos\theta).(\Delta V_i/V_i + \Delta a/a + \Delta V_k/V_k) \\
&- 2B_i.a^2.V_i^2(\Delta V_i/V_i + \Delta a/a)
\end{aligned}$$

$$\begin{aligned}
\Delta P_{ki} &= (G.\sin\theta + B.\cos\theta).(\Delta\delta_i - \Delta\delta_k + \Delta P) - (G.\cos\theta - B.\sin\theta).(\Delta V_i/V_i + \Delta a/a + \Delta V_k/V_k) \\
&+ 2G_k.V_k^2(\Delta V_k/V_k)
\end{aligned}$$

$$\begin{aligned}
\Delta P_{ki} &= (G.\cos\theta - B.\sin\theta).(\Delta\delta_i - \Delta\delta_k + \Delta P) + (G.\sin\theta + B.\cos\theta).(\Delta V_i/V_i + \Delta a/a + \Delta V_k/V_k) \\
&- 2B_k.V_k^2(\Delta V_k/V_k)
\end{aligned} \tag{2-19}$$

Equality Constraints

The equality constraints included in the optimisation have the form [52]:

$$\Delta F = J.\Delta E \quad (2-20)$$

J is conveniently the same Jacobian that is used in the standard Newton Raphson algorithm. ΔE contains the $\Delta\delta$ and ΔV variables. ΔF contains the mismatch in active and reactive powers at each node. To accurately reflect the power system problem the equality constraints should also take into account controllable shunt susceptance, phase shifter angles P , generator voltage targets, SVC voltage set-points and transformer tap positions.

Inequality Constraints

The inequality constraints on all linearised variables need to be formulated in terms of the control variables when using a compact formulation. Therefore the formulation of the linearised inequality constraints on control variables is straight forward and is given by:

$$h_{\min} - h(U, X) \leq \Delta U \leq h_{\max} - h(U, X) \quad (2-21)$$

U , h_{\min} , h_{\max} and h are vectors of the independent control variables, the minimum limits, the maximum limits and the corresponding values at the current operating point respectively. The linearised inequality constraints on other variables are formulated using the following equation:

$$h_{\min} - h(U, X) \leq [dX / dU] \Delta U \leq h_{\max} - h(U, X) \quad (2-22)$$

X is a vector of the dependent variables. Note that the limits on the linearised form are the original values shifted by the variables value at the current operating point. The derivative dX/dU relates the sensitivity of the constrained dependent variable to the control variable changes.

Other inequality constraints considered within the optimisation include the MVar branch flow, voltage change and MVar reserve on generators. The LP used in this research was a compact formulation and therefore all inequality and equality constraints needed to be specified in terms of the control variables only.

Objective Function

This research focussed on solving the active power losses minimisation problem involving reactive power controls, while fixing active power controls. The active transmission losses objective function is given by [52]:

$$Losses_{Tot}^{AC} = \sum_{L=1}^{n_L} G_{ik} (V_i^2 + V_k^2 - 2V_i V_k \cos \theta_{ik}) \quad (2-23)$$

L is a line with conductance G connecting the i^{th} node to the k^{th} node, and N_L is the total number of lines on the network. This objective function is non-separable, which means that it cannot be incorporated directly into the LP problem.

Alsac et al. [32] presented an optimisation method that can be used to solve problems involving non-separable objective functions such as the active transmission losses. LP-based methods are better adapted to solve optimisation problems that are highly separable. In order to handle the non-separable active transmission losses minimisation objective function within the LP it is necessary to perform an approximation. This approximation is achieved by building a separable objective function in terms of the control variables at the current operating point. In other words the non-linear objective-function hypersurface at the current operating point is approximated by a tangent hyperplane in a space with each axis representing a control variable.

The change in active losses is related to control variable changes by:

$$\Delta P_L = \left(\frac{\partial P_L}{\partial U} \right)^T \Delta U \quad (2-24)$$

The sensitivities dP_L/dU in the equation above can be obtained from a loss penalty factor calculation. For n controls the linear approximation of the active losses objective becomes:

$$Losses_Objective = \sum_{z=1}^n \left(\frac{\partial P_L}{\partial U_z} \right)^T \Delta U_i \quad (2-25)$$

It is necessary to perform this linear approximation of the active losses objective at each iteration of the SCORPF solution method when performing loss minimisation. The approximation is only valid over a small region, which is achieved by placing limits on the control changes. The rest of the power flow optimisation problem is linearised in the usual way and solved by the LP. Assuming that the control changes are small enough then the solution to the LP should have lower active losses. Alsac et. al. [32] developed a successful approach based on this method that dynamically varies the control change region based on the success of the previous iteration at reducing the losses.

2.3.8 Linear programming method

The overall efficiency of the SCORPF is governed by the computational efficiency of the linear programming central step that is discussed in this section. Stott and Marinho [40] describe a simplex based LP method applied to a real power optimisation problem. This technique is summarised here, as the technique is exploited within the remainder of this research. The LP constraint enforcement process begins from an optimal solution determined when all constraints are ignored. The solution to the LP will always be at some vertex of the constraint set in the hyperspace with axis corresponding to the control variables. This is because the LP method restricts itself to considering the power system operating states that are at some vertex. Each iteration of the LP moves the operating point from one vertex to the next until the solution is reached. The basis matrix equation shown below describes the power systems operating state at each iteration of the LP. B is the basis matrix and ΔU is a vector of the optimisable control variables. The first row of the basis matrix relates to the power balance equality in terms of only the controls, the other $n-1$ rows correspond to constraints that are on a binding limit.

$$L = [B]. \Delta U \quad (2-26)$$

The above equation can be arranged so that the $n-1$ non-sparse constraints appear in rows two to n . The superscripts f and l , in equation 2-27 below, relate to the free (basic) controls and the limiting (non-basic) controls respectively. The reduced basis is expanded as:

$$\begin{array}{c|c|c|c}
L^b & B^f & B^l & \Delta U^f \\
\hline
L^c & 0 & \begin{array}{c} 1 \\ 1 \\ 1 \end{array} & \Delta U^l
\end{array} = \begin{array}{c|c}
\Delta U^f \\
\hline
\Delta U^l
\end{array} \cdot \quad (2-27)$$

L^b is zero and corresponds to the power balance equality constraint and L^c is a vector corresponding to the upper/lower limits on non-basic controls. B^f and B^l multiply the basic and non-basic controls respectively corresponding to the overall power flow equality. The unity matrix in the lower RHS of the basis matrix multiplies the non-basic controls.

The LP iteration begins with the basis equation, which defines the current operating state of the power system. A set of violated constraints are chosen from the linearised constraints to be enforced by introducing them into the basis equation. To do this an existing binding constraint in the basis equation needs to be removed, which means that it is freed and relaxed. This exchange moves the system to a new operating point. The choice over which violated constraints should enter the basis is arbitrary; however a suitable method needs to be chosen to decide which binding constraint in the basis should be removed. This decision is performed by first identifying those constraints that are eligible to be removed. A constraint is eligible if when it is freed it backs off from its previous binding limit. A “ratio test” is then used to decide which of the eligible constraints when removed will minimise the increase in the objective function.

The eligibility test

To determine the constraints in the basis matrix that are eligible to be removed, it is necessary to determine the sensitivity between the incoming constraint and each binding constraint presently in the basis matrix. The sensitivity of the k 'th binding constraint in the basis is given by S_k [40].

$S_k = (\text{The amount by which the violating constraint will be corrected by entering its constraint into the basis matrix}) / (\text{The amount by which constraint } k \text{ will change when freed})$

If the incoming and constraint k are both on their upper or lower limit and S_k is positive then the constraint is eligible. If the constraints are on opposite limits and S_k is negative then the constraint is eligible. Otherwise constraint k is not eligible to be removed from the basis. If, once all constraints have been tested, there are no eligible constraints then the optimisation problem is deemed infeasible. This is because there are no constraints that can be removed from the basis without immediately causing a violation.

The ratio test

The ratio test provides a method for choosing the one eligible constraint to remove that causes the least increase in the value of the objective function. The k' th binding constraint to be removed has the smallest value of the ratio λ_k/S_k , where λ_k is the incremental cost of the constraint [40].

Determining the value of the controls at each iteration of the LP

The lower part of the basis matrix shown in equation 2-27 corresponds to non-basic controls, and can be easily solved. The top part of the basis matrix corresponds to controls that are basic, and is more difficult to solve. To determine the values of the basic controls we multiply out the first row of equation 2-27 and rearrange.

$$L^b = B^f \Delta U^f + B^l \Delta U^l \quad (2-28)$$

$$\Delta U^f = B^{f^{-1}} (L^b - B^l \Delta U^l) \quad (2-29)$$

Updating the basis and summary of LP steps

At each iteration of the LP a constraint that is in the basis matrix will be replaced by a constraint that requires enforcement. The basis matrix is always reordered to preserve the structure indicated in equation 2-27.

In general the LP proceeds by the following steps:

- 1) Compute S_k values.

- 2) Determine eligible binding constraints.
- 3) Compute the incremental cost of each of the current binding constraints.
- 4) Apply the ratio test to determine which one constraint should be freed.
- 5) Update and re-order the basis equation with the new binding constraint.
- 6) Determine the value of the basic control variables using equation 2-29.
- 7) Check if there are more violations and if necessary repeat from step 1.

The iterative LP method terminates when all constraint violations have been removed or when the optimisation problem is deemed infeasible. The next sections explain how this LP algorithm is embedded in the overall security constrained optimisation process, which is itself another iterative process.

2.3.9 Decomposed approach to solving SCORPF

The equations given in section 2.3.5 formulate the generalised SCORPF problem. The standard approach for solving the SCORPF problem has been to apply a Decomposed Approach [34]. First a solution is found to the base case master problem. The SCORPF is then augmented by a small number of individual post-contingency inequality constraints, which have been expressed in a reduced form in terms of the base case control variables using large-perturbation linearised sensitivity analysis. A compact version of the Decomposed Approach is used in this research, as it has been shown historically to be successful at solving large-scale security constrained problems.

As shown in Figure 2-7 an AC power flow calculation is performed prior to solving the main LP problem. The power flow calculation is performed for the intact network and each contingency that is on the critical contingency list. Each post-contingency constraint to be included in the optimisation is then linearised about the relevant (U^k, X^k) variables using a similar method to that described in section 2.3.7 for base case constraints. These are then transformed into a function of base case control variables U^0 using the relation:

$$U^k = A.U^0$$

A is a sparse square matrix that describes the response of the controls to the contingency case. $U^k=U^0$ for most controls with the exception of active power generation.

2.4 Summary

This chapter described the modelling that can be used to represent reactive power control devices in the SCORPF problem. The SCORPF method described by Stott and Hobson [33], Stott and Alsac [34] and Alsac et al. [32] was also presented. SCORPF based techniques will be important for future operational voltage control management, because this is currently a time consuming manual process. This chapter has introduced the fundamental principles of SCORPF, which will be important for chapters 4 to 7 of this thesis, because these chapters will assess the potential for SCORPF based techniques for practical implementation on the National Grid Transmission System.

Chapter 3

GB Transmission Network Technical, Environmental and Commercial Background

3.1 Introduction

This research aims to develop Security Constrained Optimal Reactive Power Flow (SCORPF) techniques to assist control centre operators in the dispatch of a secure, economical and low loss system voltage profile for the GB transmission system. To enable this it is first of all important to review the main environmental, technical and commercial drivers relating to active transmission losses. In the previous chapter we introduced the concept of reactive power, which is a concept directly related to the voltage optimisation process, therefore this chapter now reviews the commercial background to reactive power with specific regard to the GB transmission system.

In order to research, develop and build a prototype voltage optimisation tool it is important to review relevant National Grid optimisation tools including those that have been decommissioned. Pertinent SCORPF algorithmic, modelling and usability issues will be highlighted, emphasising how the prototype voltage optimisation tool should build upon the success of previous tools and avoid any short comings that were highlighted. A review of National Grid's offline power system analysis suite and integrated energy management system is also presented within this chapter, as it is these systems which the voltage optimisation tool will need to interface with.

This chapter presents the historical development of the SCORPF methodology and critically discusses practical implementations of ORPF in Spain, Belgium and Canada that are discussed in the literature. A wide range of literature on the subject of ORPF is available, but there is relatively little literature on SCORPF

specifically. We note that practical large-scale SCORPF studies have been performed in Belgium and in the UK, but the published results were limited in the sense that they only considered a small number of networks and a relatively low number of contingency cases.

3.2 Active Power Losses on the GB Transmission Network

3.2.1 Technical background

As discussed in chapter 1 transmission losses can be classified into two groups, variable losses and fixed losses [57]. Transmission losses on the GB transmission system can also occur due to non-technical losses. The variable losses is also known as load losses, series losses, transport-related losses, or copper losses. These losses mainly arise due to the resistance of the current flowing through a line. Equation 3-1 shows how the variable active power losses to a first order approximation is proportional to the square of the active power flow, because the voltage of a power system does not tend to deviate significantly from its nominal value and the active power flow is usually greater than the reactive power flow [57]. Eddy current in the core of transformers at right angles to the main current flow also form a component of the variable active power losses.

$$VariableActiveLosses = I_{RMS}^2 R = \left(\frac{S}{V_{RMS}} \right)^2 R = \frac{(P^2 + Q^2)}{V_{RMS}^2} R \approx \frac{R}{V_{RMS}^2} P^2 \approx K.P^2 \quad (3-1)$$

The operational variable transmission losses can be reduced by minimising branch current flow, which could be achieved by running a substation as solid instead of split. It can also be reduced by using higher voltages, balancing three phase loads and dispatching generation closer to demand centres [12].

The fixed losses is also known as shunt losses or iron losses. Transformers fixed losses is present whenever a transformer is energised. These losses have two components, the first results from taking the core through successive cycles of magnetisation leading to hysteresis, and the second results from eddy currents in the core [5].

The corona of overhead lines can give rise to fixed losses [58]. Corona losses occur because the electrical field around a conductor can cause a partial breakdown of the air and therefore cause the production of ions that carry energy away from the transmission line. This phenomenon is dependent on the voltage level, the ambient atmospheric conditions surrounding the transmission line, the frequency and waveform of the supply, the configuration of the conductors, the height from the ground and the type of conductor that is used.

Other components of fixed losses include dielectric losses, radiation, induction, open-circuit losses and losses caused by the continuous operation of power system measuring control systems.

Fixed losses have a weak dependence on the power flow. These losses are proportional to the square of the voltage on the network, and therefore to a first order approximation can be regarded as constant, assuming the voltage profile of the system is fairly constant. In the case of a transformer's fixed losses this quadratic relationship with voltage can be understood by modelling the transformer with a finite conductance and susceptance. The real and reactive power losses associated with these characteristics are shown below [37]:

$$\begin{aligned} P &= GV_{RMS}^2 \\ Q &= BV_{RMS}^2 \end{aligned} \tag{3-2}$$

The third type of losses is known as the non-technical losses. These losses include power that is stolen at any point on the high voltage transmission network. Other losses that belong in this category include metering errors, and unmetered substation supplies [5].

This project is concerned with proposing reactive optimisation techniques for securely reducing the operational fixed and variable transmission losses that occur on the GB transmission network. Table 3-1 shows that the active transmission losses, as a percentage of demand, occurring on the GB transmission network is forecast to increase between 2012 and 2015. Part of this increase is due to the

connection of renewable generation in Scotland, which will increase the north-south power flow [6]. Interestingly there is a small reduction in active losses in the period from 2010 to 2012, which is due to the commissioning of new generation in the south that will reduce the north to south flow.

	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15
Transmission Heating Losses excluding GSP Transformers (MW)	760	912.5	884.3	930.2	915.8	1090.1
Fixed Losses (MW)	273	276	276	276	282	284
GSP Transformer Heating Losses (MW)	103.2	108.4	112.7	118.8	121.2	129.3
Generator Transformer Heating Losses (MW)	103.4	111	108.2	137.4	133.2	135.8
Total Losses	1239.6	1407.9	1381.2	1462.4	1452.2	1639.2
ACS Peak Demand (MW) excluding Losses and Station Demand	58145.6	58774	59512.1	60194.4	60637.2	61129.9
Total Losses as percentage of Demand	2.1	2.4	2.3	2.4	2.4	2.7

Table 3-1. Active Power Losses at Peak Demand [6]

3.2.2 Environmental context

A reduction in active losses on the GB transmission network translates into a reduction in the marginal generation, which is usually fossil fuel based. In general the coal power industry, which makes up 36% of the UK's generation mix [6], produces a significant fraction of the UK's acidifying and greenhouse gas emissions [59]. Power station emissions of sulphur dioxide and nitrogen oxides account for the biggest share of the UK's acidifying emissions. These emissions can cause acidic precipitation that leads to increased soil acidity damaging aquatic life, crops, plants, buildings and other manmade structures. Sulphur dioxide emissions are now falling due to the Large Combustion Plant Directive (LCPD) that places tighter controls on coal burning, encourages the use of low sulphur coal, and the use of abatement equipment [60].

So far we have considered the environmental benefit of loss minimisation in terms of the reduction in emissions from power stations during electricity generation. Emissions can also occur at all points during the life cycle of a power station and all points during the life cycle of the fuel that is being burnt. For example during coal mining methane, which is a green house gas, is released. Therefore the whole life cycle of a power station and the fuel that is being burnt needs to be considered when determining the full benefit of loss minimisation.

It is useful to define a ‘carbon footprint’ for each generation technology, which is an environmental impact measure in units of grams of CO₂ equivalent per kilowatt hour of generation (gCO₂eq/kWh) [61]. It is important to note that ‘equivalent’ means that all greenhouse gases are included when accounting for the global warming effects of each kWh. All electricity generation systems have a carbon footprint when considering the environmental impact of the construction, operation, and de-commissioning phases. A useful method to assess relative environmental performance is to rank generation technologies in the order of their respective carbon footprint sizes. A carbon footprint can be calculated using a ‘cradle-to-grave’ approach which considers the impact on the environment from all phases of its life. It accounts for inputs and outputs to the environment [62]. This method is based on the accredited ISO 14000 standard.

The second column of Table 3-2 shows the carbon footprint of the major fuel types listed in the first column. These carbon foot prints have been determined by using the cradle-to-grave approach described above. The third column shows the fuels percentage contribution to the generation mix and the fourth column shows the calculated total losses carbon footprint over the entire year, which is determined by multiplying the total losses in 2008/9 by the carbon footprint and the corresponding generation mix. The total *carbon footprint* of losses over the year is therefore equivalent to 3.4 million tonnes of CO₂. This value will be useful in later chapters when determining the environmental savings resulting from active losses optimisation.

Fuel	Approx Carbon Foot Print (gCO ₂ eq/kWh)	Generation Mix (%)	Carbon Footprint of losses in 2008/9 (kT CO ₂ eq/kWh)
Nuclear	5	13	3.9
Wind	5	3	0.9
Hydro	20	3	3.6
Gas	500	35	1050
Oil	650	4	156
Coal	1000	36	2160
Other	-	1.2	-

Table 3-2. Carbon footprint of different fuel types. Data is sourced from Parliament Office of Science and Technology [61] and BERR [63].

The World Resources Institute's Greenhouse Gas Reporting Protocol [64], recommends that greenhouse gas emissions are reported in three 'Scopes'. Scope 1 are direct emissions from sources owned or controlled by the company, Scope 2 are indirect emissions from sources such as the emissions associated with the purchase of electricity and Scope 3 include other indirect emissions. National Grid has classified transmission losses as Scope 3 emissions due to the limited control the company has over these emissions [65]. The reasoning behind this is that the company has no control over generation fuel type and limited control over generator location, which are factors that strongly influence the level of transmission losses. The magnitude of transmission losses that occur on the network is also influenced by the voltage profile; the voltage profile is the magnitude of the voltages measured at cardinal busbars across the network. The research presented in this thesis makes use of the sensitivity of the losses to the network's voltage profile, thereby allowing the potential for secure optimisation techniques to be implemented into practice.

3.2.3 Active transmission losses charging

The Central Data Collection Agency (Elexon) collects metered data from generators and demand [5]. There will always be a mismatch between total metered generation and total metered demand over any given half hour settlement period, this difference is equal to the active losses. All energy needs to be accounted for, so the cost of active transmission losses needs to be allocated to the

liable parties. Active transmission losses is allocated to each Balancing Mechanism (BM) unit, a BM unit could for example be an individual generator. A collection of one or more BM units are known as a Trading Unit. Over a Settlement Period if the Trading Unit is a net exporter of electricity then the Trading Unit is termed as a delivering Trading Unit. If the Trading Unit is a net importer of electricity over a Settlement Period then the Trading Unit is termed as an offtaking Trading Unit. Within the BM for each settlement period active transmission losses is defined as the difference between the absolute metered volumes of all delivering Trading Units and offtaking Trading Units [66].

$$TransmissionLosses = \sum^{+} QM_{ij} + \sum^{-} QM_{ij} \quad (3-3)$$

QM_{ij} is the BM Unit Metered Volume for a BM Unit i in settlement period j .

\sum^{+} is the sum over all BM Units that are part of delivering Trading Units (has +ve value).

\sum^{-} is the sum over all BM Units that are part of offtaking Trading Units (has -ve value).

To account for active transmission losses each BM Unit's metered volume needs to be adjusted. This can be achieved by multiplying the metered reading by a Transmission Loss Multiplier (TLM). This multiplier has two components, a Transmission Loss Factor (TLF) and an adjustment factor that depends on whether the BM Unit is an offtaking Trading Unit or a delivering Trading Unit.

At present the $TLFs$ are all set to zero. These factors maybe used in the future to vary the weighting on the transmission losses costs allocated to individual BM Units depending on its geographic location. Therefore each TLM is identical for all BM Units that are offtaking Trading Units; similarly each TLM is identical for all BM Units that are delivering Trading Units. The following equations define the TLM :

$$TLM_{ij} = 1 + TLF + TLMO_j^{+} \quad \text{for all BM Units that are part of delivering Trading Units.}$$

$$TLM_{ij} = 1 + TLF + TLMO_j^{-} \quad \text{for all BM Units that are part of offtaking Trading Units.}$$

The $TLMO$ are given in equation 3-4.

In each settlement period a proportion of the transmission losses cost is allocated to each of the BM Units depending on whether it is a delivering Trading Unit or an offtaking Trading Unit. The Balancing and Settlement Code (BSC) defines a parameter α that is used to determine the values of $TLMO_j^+$ and $TLMO_j^-$. α is the allocation of transmission losses to delivering Trading Units. For example if $\alpha=0.5$ the transmission losses is allocated equally between Delivering Trading Units and offtaking Trading Units. In practice $\alpha=0.45$ is used so that the delivering Trading Units are allocated slightly less of the losses cost than the offtaking Trading Units. This allocation is used to account for the fact that generators pay for losses that occur in their high-voltage transformers, because they have their energy metered on the high voltage side of their transformer. Conversely the offtaking Trading Units are allocated a slightly higher proportion of the transmission losses (0.55) because they have their energy metered on the low voltage side of their transformer.

With each TLF set to zero, and $\alpha=0.45$, the equations describing the $TLMO_j^+$ and $TLMO_j^-$ are:

$$TLMO_j^+ = -0.45 \frac{\left(\sum^+ QM_{ij} + \sum^- QM_{ij} \right)}{\sum^+ QM_{ij}} \quad TLMO_j^- = 0.55 \frac{\left(\sum^+ QM_{ij} + \sum^- QM_{ij} \right)}{\sum^- QM_{ij}} \quad (3-4)$$

Notice that the numerator is actually the losses. For any given settlement period the expected value of TLM for a delivering Trading Unit would be less than one, while for an offtaking Trading Unit it would be greater than one.

In every settlement period there are just two values of the TLM calculated by the Settlement Administration Agent corresponding to delivering and offtaking Trading Units. The TLM can then be used to scale each BM Unit's Metered Volumes.

The cost associated with the active transmission losses is therefore picked up by the users of the transmission system e.g. generators and suppliers. These costs are ultimately passed onto the electricity consumer.

3.2.4 Balancing Services Incentive Scheme

The New Electricity Trading Arrangements (NETA), introduced in March 2001, replaced the Pool based system [76]. These arrangements decentralize the sale of electricity with most electricity being sold through individual bilateral contracts and through organised markets that have balancing arrangements to deal with real-time fluctuations in supply and demand. The Balancing Mechanism (BM) is the tool used by National Grid to balance the supply and demand of electricity close to real time. The BM costs money to operate and National Grid is incentivised to reduce these costs [13].

In 2009/10 National Grid and Ofgem agreed a Balancing Services and Incentive Scheme (BSIS). Within this 12 month scheme National Grid is set a target operating cost, known as the Incentivised Balancing Costs (IBC). If National Grid manages to keep the annual balancing costs below the IBC target value then they are allowed to keep a proportion of the difference. This proportion is known as the ‘upside sharing factor’. On the other hand if National Grid’s costs exceed the IBC target value then they are penalised, as they have to pay a proportion of the excess costs. This proportion is known as the ‘downside sharing factor’. The IBC is a summation of several components, one of which relates to active transmission losses. A simplified formula describing the IBC is shown below [13]:

$$IBC = CSOBM + BSCC + TLIC - NIA \quad (3-5)$$

- *CSOBM*: Daily System Operator Balancing Mechanism Cash Flow.
- *BSCC*: Balancing Services Contract Costs.
- *NIA*: Net imbalance Adjustment.
- *TLIC*: Transmission Loss Adjustment. See below.

The active transmission losses adjustment (*TLIC*) is a component of the incentivised balancing costs, which is given by the following equations:

$$\begin{aligned}
TLIC &= TLRP*(TL - TLT - 0.2TWh) & \text{when } TL - TLT > 0.2 TWh \\
TLIC &= TLRP*(TL - TLT + 0.2TWh) & \text{when } TL - TLT < 0.2 TWh \\
TLIC &= 0 & \text{when } |TL - TLT| < 0.2 TWh
\end{aligned}$$

$$TLRP = £55/MWh \quad \text{in 2009/10 [67]}$$

The Transmission Losses Target (TLT) is currently calculated at the beginning of each year and is then updated every three months.

3.3 GB Transmission Network Operational Voltage Control

3.3.1 Reactive balance

In this section we will consider operational voltage control issues from the perspective of the GB transmission network operator. The reactive balance concept is important to the overall voltage control strategy, which must maintain a balance between MVARs that are generated and MVARs that are absorbed by the system. Generation of MVARs can be achieved through the switching of shunts, by issuing instructions to generators and by changing the settings of SVCs / synchronous compensators. The capacitance and inductance connected to the transmission system can also be exploited by ENCC engineers to improve the voltage control. A lightly loaded line will often act as a capacitive network element that will inject MVARs, while a heavily loaded line will act as an inductive network element that will absorb MVARs. The formula below is the reactive balance equality [68].

$$\begin{aligned}
&Generated_MVAR + System_gain_BV^2 + Shunt_capacitors_BV^2 = \\
&Demand_MVAR + System_reactive_losses_I^2X + Shunt_reactors_I^2X
\end{aligned}
\tag{3-6}$$

3.3.2 Reactive market

The Grid Code, which National Grid and users of the transmission system must comply with, describes the requirement on generators to provide a reactive power capability. At any given MW output, a generator can be requested to absorb or

produce reactive power to help manage the system voltage profile. The requirement specifies that each generator must be able to operate at a power factor within the limits of 0.85 lagging and 0.95 leading at its terminals [69]. National Grid ensures that reactive power is provided to meet the constantly varying needs of the system and ensures that reserves are adequate to meet any credible contingency. In the reactive market each commercial entity providing reactive power support is paid at an agreed amount based on the *volume* of reactive support that is provided. Each Balancing Mechanism (BM) unit defines a commercial entity, and typically consists of several generators capable of providing reactive power support to the network.

Assuming all BM units are paid at the default price, the total reactive utilisation payment is:

$$\text{Payment} [\pounds] = Qvolume[MVArh] * price[\pounds / MVArh] = \left| \sum_{i=1}^n lag_i - \sum_{i=1}^n lead_i \right| * price \quad (3-7)$$

n is the total number of generators comprising the BM unit, $lead_i$ is the metered leading reactive energy in units of MVArh, lag_i is the metered lagging reactive energy in units of MVArh, $price$ is the default utilisation payment in units of $\pounds/MVArh$, and $Qvolume$ defines the total reactive volume from the group of generator units in units of MVArh. The default price for generator reactive utilisation in the summer of 2010 was $\pounds 2.47$ per MVArh [70]. In 2009/10 most generators were paid at this price, so the assumption that was made is acceptable in most cases. It is important to note that Equation 3-7 defines the objective function that needs to be minimised in a reactive costs optimisation problem.

National Grid is incentivised under the incentive scheme described in section 3.2.4 to minimise spend on the reactive payments to generators. The BSCC component in Equation 3-5 includes these reactive payments. Annually National Grid and Ofgem agree a reactive costs target as part of the overall incentive scheme.

3.3.3 Security and Quality of Supply Standard

National Grid holds the sole licence to operate the transmission network in England, Wales, and Scotland, and therefore has a responsibility to maintain an efficient, economical and co-ordinated GB Transmission System [6]. The operational planning process involves preparation of detailed operational plans from around 13 weeks ahead of real time, and includes manual optimisation of the network's voltage profile taking into account all planned outages due to the maintenance and construction work that is happening on the transmission system. This process ensures that the GB National Electricity Transmission System Security and Quality of Supply Standard (SQSS) requirements are satisfied economically in the network plans [3]. One of the major deliverables is a secured day-ahead peak demand network study, which is the focus of this research. These studies are adjusted for each day to take account of changes in predicted demand, generation and outage pattern. A hand over document is prepared and delivered to the ENCC, which includes network plans, outages, active constraints on MW flows, and post-fault actions to be taken in the event of contingencies. While the emphasis of the day-ahead deliverable is on active power management there is an SQSS requirement to secure voltage, which means that reactive power management is considered. The SQSS also includes regulatory requirements relating to generation margin, frequency control, voltage condition and thermal overload conditions [3]. These requirements must be carefully considered within this research, as reactive controls are manipulated by the optimisation algorithm. It is essential to ensure that available dynamic reactive reserves are maintained on SVCs and generators in order to secure the post-fault system voltages in the event of the most onerous credible fault. The steady state voltage condition must be secured both pre and post fault, as shown in Figure 3-1 below. This figure shows the SQSS voltage requirements at customer and non-customer connected buses. Customer buses include grid supply points to the low voltage network. The steady state voltage limit information is also indicated at each voltage level, the network must be secured so that it can meet these standards for both the intact network and in the case of an unexpected outage. At customer connections the voltage must not change more than the regulated limits shown in the event of either a single circuit (SC) or double circuit (DC) outage. Distribution Network Operators (DNOs) in

England and Wales connect at 132kV, these networks then feed down to lower voltage levels.

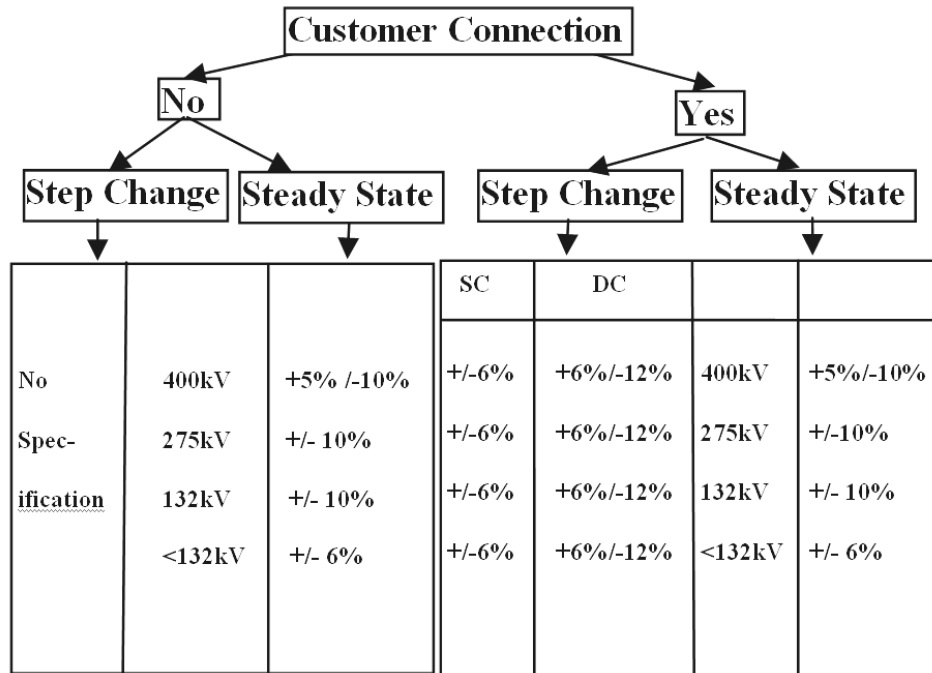


Figure 3-1. Acceptable voltage conditions on the GB HV transmission system. SC=Single circuit outage, DC=Double circuit outage [3].

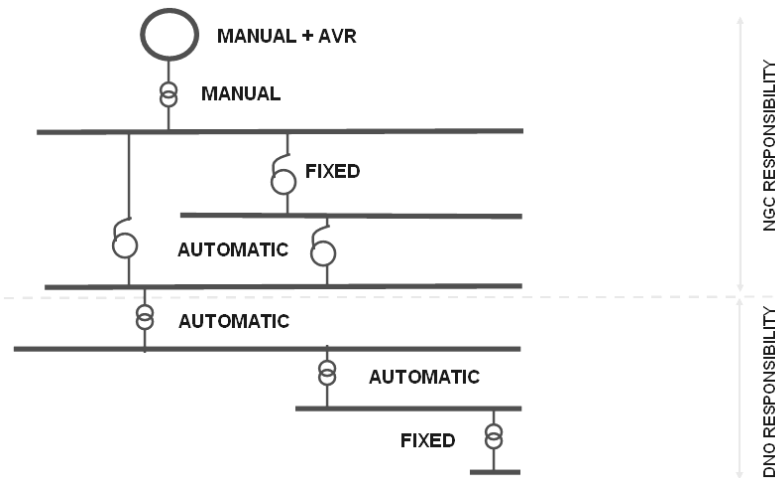


Figure 3-2. Levels of voltage control across the HV transmission network.

3.3.4 Offline network voltage planning

The Transmission Requirements (TR) Optimisation Team prepares secure and economical outage plans from the thirteen week-ahead stage for eventual handover to the Delivery Team at the three week-ahead stage. The Optimisation Team continually update a database of outages with information such as the re-switching required during a particular week. The TR Optimisation Team also

perform powerflow studies to simulate credible contingencies that could occur on the system. [13]

The Delivery Team then produce a day-ahead study for each weekday and weekend day. These day-ahead studies are determined for a single cardinal point in demand. The ENCC Transmission Analysis Engineer (TAE) modifies these day-ahead studies to secure for other cardinal points during the day.

Throughout the entire production process the reactive dispatch in the offline network plans may be modified to obtain a secure voltage profile. The power system engineer will consider the following factors when setting up a good voltage profile:

- Utilisation of reactive power from shunt capacitors and reactors before using generator reactive power.
- Keep reactive generation close to float (zero MVar output) where possible.
- Avoid circulating MVAr.
- Maintain adequate reactive reserve and response.
- Remove voltage limit violations in base and contingency cases.
- Remove voltage change violations in contingency cases.
- If necessary request additional generators to provide voltage support in order to secure the voltage.

The process of finding a good voltage profile is a manually repetitive process. First the planner will run an AC power flow, they will then check the voltage conditions by reading the output log, and perform reactive switching as necessary to move towards a more desirable voltage profile. This will be repeated several times, as the system does not usually behave linearly. Finally the planning engineer will obtain a network voltage profile that is secure against a wide range of credible contingency cases.

3.3.5 Real-time transmission network voltage switching

The offline TAE planning studies, which are designed to be secure at a cardinal point in time, are used to generate target voltage profiles. The transmission dispatch engineer (TDE) dynamically switches reactive equipment and issues MVar instructions to generators in order to ensure system security and adequate MVar reserves, while using the target voltage profile as a guide [71]. The reactive switching decisions will be heavily influenced by the anticipated changes in future demand. Each of the offline TAE studies will have been securely configured at a snap-shot in time, and provide no information to the TDE on how to evolve the network from one moment to the next. This highlights the key difference between off-line snapshot studies that are secure for a given generation/demand/outage pattern, and the real time system that is dynamic.

To support the voltage during the morning demand pick-up, which is typically between the hours of 5:30AM and 9AM, reactors will be switched out and capacitors will be switched in. When possible generators will be ordered to move to zero reactive power output or where necessary they will be ordered to produce reactive power in order to maintain system voltage security pre and post fault. During the evening demand drop off a reverse of the above procedure is implemented with reactors being switched in and capacitors being switched out.

3.3.6 ELLA power analysis tools

ELLA is a platform that gives users access to a range of power system analysis tools and allows for the management of network data [72]. Typically the full GB transmission network model can be manipulated from within ELLA, this model includes data for the transmission network and parts of the low voltage DNO network.

The tools that are available from within ELLA include AC and DC power flow analysis programs, a fault level analysis program and a stability analysis program. The most relevant tool to this research is the AC power flow program, which solves the power flow in the base case and contingency cases using the Newton-Raphson method described in section 2.2.3. This AC power flow program uses a

single phase representation of the transmission network and models the power flow under balanced conditions. The impedance parameters of the circuit elements are modelled as positive phase sequence values. ELLA is currently used at all timescales within National Grid from long term planning down to control centre time scales to assess system voltage security.

ELLA network data is stored and passed between its respective tools in the form of ASCII text using a node and branch level model. Storing the network data in this form makes it very convenient to read and manually modify. A significant disadvantage is that any important changes to the model, such as the correction of erroneous line data, needs to be made to each of the individual network data files.

3.3.7 Offline Transmission Analysis Tool (OLTA)

National Grid acquired a corporate license for DIgSILENT's PowerFactory analysis software in 2006 [73], the National Grid version of PowerFactory is known as OLTA, which is an abbreviation for Off-Line Transmission Analysis. When OLTA "goes live" it will directly replace ELLA.

The need for an ELLA replacement has arisen due to the age of the current software and the need for accurate wind farm modelling. ELLA was originally developed in FORTRAN during the 1980s [72]. At present wind farms are represented by an unregulated bus within the ELLA model, this can lead to inaccuracies in the power flow solution. The advantage of OLTA is that the program includes an accurate representation of wind farms, a detailed switch level substation model and a more familiar Windows interface. OLTA also introduces a single database concept that stores the transmission network model using an object orientated database approach, this improves data organisation and avoids the user having to convert data from one program to another [74]. One important feature of OLTA is that it allows the data administrator to release baseline models that users can use as a starting point for their own projects. At a later point in time, an updated version of the baseline model can then be released by the data administrator allowing each user to merge in the updates into their own project. This database approach represents a significant improvement over the ASCII text

approach that was used is ELLA, as it is more flexible and allows global network changes to be rolled out across all users more rapidly. OLTA can be executed in a stand-alone mode or in a multi-user mode. At National Grid the vast majority of users will use the program in the multi-user mode. OLTA data will be stored on a central Oracle database, which will be accessible to users with the appropriate access rights. When network data is requested by third parties OLTA allows data to be exported in a variety of popular data formats including CIM (IEC 61970-301), which is being used increasingly for standardised data exchange. Although CIM standards are still being developed, PowerFactory supports CIM import and export [74].

It is anticipated that offline optimisation will need to be performed from within the OLTA environment, which will either need to call an internal OLTA optimisation routine or interface with an external optimisation program. At present there are no SCORPF functions available internally within OLTA. OLTA does however include the following optimisation objective functions that are solved using a linear program and can include contingency case constraints [74]:

- Minimisation of generation fuel costs
- Minimisation of tap deviations pre and post fault
- Minimisation of generation fuel costs + tap deviations
- Minimisation of generation dispatch change.

OLTA also includes the following optimisation objective functions that are solved using a non-linear program using the interior point method, but the user cannot include contingency case constraints:

- Transmission loss minimisation
- Maximisation of profit
- Minimisation of generation fuel costs
- Minimisation of load shedding

The transmission losses minimisation objective is the most relevant to this research, but because contingency case constraints cannot be included the usefulness of this function is significantly reduced. A second limitation of using

OLTA for this research is that National Grid does not currently own a licence to use OLTA's reactive OPF functions. These limitations combined with the fact that OLTA hasn't been fully productionised means that the focus of this project has been to demonstrate SCORPF technologies interfacing with ELLA.

3.3.8 Integrated Energy Management System (IEMS)

The Integrated Energy Management System (IEMS) is the central control centre system to monitor, control and optimise the transmissions system and connected generation [18]. The monitoring and control functions are known as a supervisory control and data acquisition (SCADA). The IEMS includes displays showing the current state of the network such as the line, transformer, busbar, circuit breaker and isolator statuses. Periodically at ten minute intervals the Power Network Analysis (PNA) tool, which runs on the IEMS, performs contingency analysis and generates a system snapshot file in the IEEE common format. Warning alarms are then issued notifying the operator to limit violations in the base case or contingency cases, who then has the opportunity to take corrective actions. The IEMS, which is a customised application provided by GE, has recently finished undergoing major upgrade works including a new front end. At present the IEMS does not support the CIM power data standard, but there are plans to enable support for this format in the future. This will allow for increased interoperability with existing and future control room systems, such as the new Market Management System that is replacing the existing Balancing Mechanism system.

3.4 GB Transmission Network Operational SCORPF

3.4.1 National Grid operational optimisation tools

There is currently a shortage of operational reactive optimisation tools deployed in practice within National Grid operations. As indicated in the introduction the anticipated 2020 power network will be more challenging to operate due to larger swings in system power flow, there is therefore a need to perform research and development to develop techniques for deploying secure power system optimisation tools into practice [1]. This section will review National Grid's past and present active and reactive optimisation tools. Where appropriate explanation

will be given to the reasons why these tools were withdrawn from service, so that future optimisation tools can avoid the same issues.

3.4.2 SCOPE – Power system analysis and optimisation

SCOPE is an SCORPF program that has formed the basis of all reactive optimisation tools that have been available at the ENCC. SCOPE has been used because it is one of the few commercially available tools that can solve the full SCORPF problem. SCOPE provides a flexible macro language that allows highly customised optimisation routines to be programmed, and also allows a wide number of objective functions, constraints and controls to be defined [39].

Relevant objective functions available in this software include:

- Loss minimisation
- Reactive cost minimisation
- Remedial control action by minimum control action
- Remedial control action by minimum control shift

Relevant constraints include:

- Control limits
- MVAr branch flow limits.
- Voltage limits.
- Voltage change limits.
- Generator MVAr reserves.

Relevant controls include:

- Generator voltage targets.
- SVC voltage set-points.
- Discrete shunt capacitors.
- Discrete shunt reactors.

This research utilises the SCOPE program because of the features and flexibility it offers. The SCOPE program also provides the most mature and robust SCORPF algorithms available, and could therefore form the basis of a practical SCORPF control centre tool.

3.4.3 ACCORD – AC security constrained optimal reactive dispatch control centre tool

The ENCC temporarily implemented a secure reactive optimisation tool called ACCORD (A Contingency Constrained Optimal Reactive Dispatch) [71]. ACCORD was designed to provide contingency secure solutions and was implemented at National Grid during the mid-1990s. Several objective functions were available including a control action minimisation objective. ACCORD was only able to secure against 20 contingency cases, therefore the Reactive Management Engineer (RME) was expected to select 20 cases out of all the possible cases, which could be more than 1000. After convergence was achieved the solution was transferred to the IEMS display and acted as a voltage target for the TDE. Information was also shown to the TDE indicating the required reactive reserve on generators and SVCs needed to ensure post fault security.

The ACCORD process confirmed the understanding that it is important to maintain adequate reactive reserves within defined groups. The program reduced the time consuming work needed to set-up the voltage profile. Experience with the ACCORD optimisation solutions showed that the voltage profile was considerably more robust than the solutions that could be produced using other methods. The robustness was evident in the reduced post fault voltage step and high post fault voltage profile [71].

One problem with ACCORD was that it could not detect an infeasible problem without running through the entire optimisation process. If the optimisation problem was infeasible, the optimisation would run to the maximum number of iterations, which could take up to 20 minutes. ACCORD normally took between 3 and 20 minutes to run. The operator was required to check and understand all convergence messages to identify an infeasible problem early on.

Although initial operator experience using ACCORD was favourable the following limitations meant that ACCORD was eventually withdrawn from service [71]:

- ACCORD did not optimise discrete controls such as capacitors or reactors. For many studies the shunts need to be optimisable in order to achieve the required secure voltage profile.
- ACCORD was limited to considering only 20 contingency cases at a time. A final contingency analysis was performed after the main optimisation, which would flag up issues to the engineer. The engineer then needed to manually secure the remaining contingencies.
- ACCORD did not include reactive cost information.
- Setting up and using ACCORD was complex and required a high level of specialised expertise to really understand it.
- ACCORD was seen as an opaque tool, basically a black box that could not be understood.
- ACCORD sometimes experienced convergence problems.
- ACCORD did not model changing demand levels as it was a snapshot optimisation. The solution may be secure at the designed point, but not two hours later.
- Transmission losses minimisation was not an option in ACCORD

Lee [71] stated that ACCORD was based solely on optimising offline study data, which was often not representative of the real system. The report stated that ‘The long term aim must be to develop the algorithm so that it can run on-line in conjunction with the PNA as effectively a contingency constrained voltage scheduler’.

The research presented in this thesis will attempt to address some of the above issues with ACCORD that lead to the tool being withdrawn from service. In later chapters novel techniques will be proposed for achieving practical transmission losses minimisation and reactive cost minimisation.

3.4.4 COLDSTART – AC security constrained optimal reactive dispatch planning tool

Coldstart was designed to be used at the beginning of the operational planning process from 13 weeks ahead of real time to set up a new secure voltage profile for a transmission network model that had been designed to represent a particular time and date [75]. Coldstart was meant to reduce the number of man hours by removing the iterative work needed to achieve an acceptable voltage profile. The operation of Coldstart is indicated by the flow diagram in Figure 3-3. The following processes occur when the Coldstart program is called by the user:

- 1) A list of shunts in service is requested from the user.
- 2) The ELLA network data is converted into SCOPE data format with all shunts modelled as in service.
- 3) SCOPE performs an initial load flow, and contingency analysis.
- 4) SCOPE then performs reactive optimisation with the selected objective.
- 5) Reactive controls are adjusted using a linear programming (LP) technique to secure the network using a minimum control shift technique.
- 6) The network data is then converted back into ELLA network data.

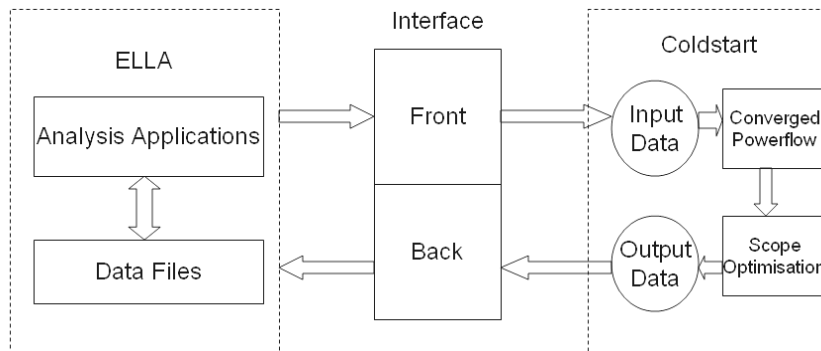


Figure 3-3. Coldstart Input, Output and Operation.

The loss minimisation projects performed by Bennett [18] and Bansal et al. [13] utilised Coldstart as the sole interface to SCOPE. The research presented in this thesis only utilised the core conversion process of Coldstart in the first stage of the optimisation. Additional modelling steps are now included, as well as a highly customised optimisation step. This alternative approach was required because conversion, modelling and optimisation issues lead to inaccurate data and erroneous optimisation results. Analysis of the Coldstart optimisation process has revealed that it was not robust enough to cope with a wide variety of different test

networks and long solution times occasionally occurred. Non-convergence and final solution infeasibility was also noted to be a problem. Rigorous analysis, testing and examination of Coldstart, and its source code, revealed the following modelling issues:

- The initial shunt switching configuration in the ELLA and Coldstart data did not agree.
- The ELLA and Coldstart network gain data values did not agree.
- The Coldstart network local voltage controls caused conflicts, because each shunt was flagged as controlling the same node.
- Discretization of controls caused final solution violations.
- Array size limitations meant that Coldstart could not be used to optimise the full GB network and the number of contingencies that could be included was limited.
- Large differences in the ELLA power flow and Coldstart power flow were discovered, which was found to be due to data issues.
- The ELLA and Coldstart network data initial generator voltage targets did not agree.
- The ELLA and Coldstart network data initial SVC voltage set-points did not agree.
- The ELLA and Coldstart network data initial transformer tap ranges were different.
- A minimum line impedance was assumed by COLDSTART, which lead to significant differences in the reactive power flow results.
- Coldstart tried to use ineffective controls to remove violations during the optimisation process.
- Coldstart did not interface with the equipment outage database, so it could not automatically identify out of service shunts.

The research presented in this thesis addresses all of the above issues in order to ensure that the network model is accurate and to ensure optimisation reliability. These issues needed to be addressed because any practical optimisation tool needs to be robust and reliable against a wide variety of different network test cases.

Informal interviews with experienced ENCC engineers revealed that the Coldstart optimisation tool managed to achieve good results in terms of rapidly creating a reasonable voltage profile. However they also stated that a significant amount of time needed to be spent reviewing and correcting the optimised network study, which may have been due to the issues highlighted in the bullet points above.

3.4.5 DISPATCH – Active generation scheduling advice algorithm

The British Electricity Trading and Transmission Arrangement requires generators to self dispatch active power rather than be centrally dispatched by the System Operator [76]. Bilateral trading between generators and suppliers stops at gate closure, which is one hour before the start of the half-hour interval in which delivery will occur. After gate closure an active power Balancing Mechanism is managed by National Grid to ensure that supply and demand can be continuously matched in real time. The active power dispatch performed through the Balancing Mechanism makes up only three percent of the total energy dispatch on average. An advisory tool called DISPATCH produces advice showing the merit order of generators that can be purchased on or off without causing constraint violations. DISPATCH uses an optimisation that is based on a LP, which optimises participating generators within generator group constraint limits. The values of the group constraint limits are periodically updated using the calculated power flows from the Power Network Analyser (PNA). This active power optimisation tool has been successfully deployed and is regularly used for the dispatch of real power. DISPATCH is being replaced with a secure DC OPF energy balancing tool, which will run in real time and model the full network, and will form part of the new market management system. The DC OPF tool will be able to run in either a preventative mode whereby the solution is secure for the intact network and contingency cases, or it can run in a corrective mode whereby the solution is secure in the intact network case with post-fault actions determined to secure each contingency case.

3.5 International Optimal Voltage Control Experiences

3.5.1 Spanish transmission network

Ramos et al. [77] applied an ORPF technique to the Spanish transmission network, which typically contains 775 buses, 1200 branches and 180 generators. Ramos et al. minimised active transmission losses by adjusting the following controls: generator voltage targets, transformer taps and switchable shunts. Inequality constraints were placed on the bus voltages, controls, generator reactive power output, and transformer flows to limit over loading. Equality constraint variables were also applied to the optimisation to represent the physical power flow.

Ramos et al. developed the optimisation problem using a primal-dual interior point technique. A non-linear optimisation problem was formulated and an appropriate starting point was determined. Non-linear optimisation was used because it was able to achieve a bigger improvement in the objective than LP. A variety of results are presented in the paper including losses vs. iteration number, power mismatch vs. iteration number, losses vs control variable type and load voltage throughout the network. Ramos et al. observed an active loss reductions of around 3% on the Spanish transmission network.

The study was comprehensive and demonstrated that ORPF can be successfully applied to improve the reactive dispatch of a practical power network. Contingency case constraint limits were not included in the proposed optimisation method, which was one of the main shortcomings of this investigation significantly limiting the potential for practical implementation. Also there were no results showing the proposed techniques robustness over a range of network test cases with the same optimisation parameters. Therefore the robustness of the technique was not proven. In addition to these practical concerns Ramos et al. did not explain if any attempt had been made to correctly handle device discreteness.

3.5.2 Belgium transmission network

Karoui et al. [78] describes the Integrated Power System Optimizer (IPSO) software, which uses the KNITRO algorithm, to solve a voltage control problem on the Belgium transmission network. This network consists of 2351 busbars and 4587 branches. Controls and constraints were very similar to those described in section 3.5.1. The objective function of the optimisation was minimum control shift away from defined control target values.

The main advantage of the technique utilised by Crisciu and Jottrand was that their method was security constrained and therefore considered the selected contingency cases. Crisciu and Jottrand also proposed a method for handling discrete devices. All devices were treated as continuous in the first stage of the optimisation. A second stage of optimisation was then performed with every shunt device frozen at a discrete step after which continuous transformer tap controls were frozen to their nearest discrete value. A third and final stage of optimisation was then performed with only the continuous controls.

The obvious disadvantage with the results presented by Crisciu and Jottrand is that their method was only tested on a single network test case with a small number of contingencies. This raises the same issue of robustness that was discussed in the previous section. Any practical SCORPF technique needs to be extremely robust against a wide range of test cases under different network conditions and network configurations. Crisciu and Jottrand have not demonstrated their SCORPF method with other objective functions such as active transmission losses minimisation and reactive costs minimisation.

3.5.3 New Brunswick transmission network

Salamat Sharif et al. [79] describe an optimal reactive power flow technique that is designed to optimise real-time system snapshots. The active losses minimisation objective was demonstrated to achieve an average saving in transmission losses worth approximately \$1.1m on the New Brunswick power network in Canada. This saving in transmission losses was also accompanied by an improvement in the voltage profile such that fewer violations were present in

the optimised solution. The investigation randomly selected a sample of hourly demand points across 1995 such that the optimisation result was statistically significant across the entire year. Controls and constraints were very similar to those described in section 3.5.1. The results presented by Salamat Sharif et al. show that the average active power losses saving ranged from around 6% to 12%. Salamat Sharif et al. note that the voltage profile is generally increased by the optimisation and that the adjustment of the control variables needs to be practical.

The work performed by Salamat Sharif et al. demonstrates the value of using ORPF to reduce power losses. However there are several issues that limit the practicality of their proposed technique. The first issue is that contingency case constraint limits were not considered in their optimisation. Salamat Sharif et al. note that the inclusion of other constraints may have substantially reduced the loss savings that they achieved. The second issue is that the treatment of discrete variables is not explicitly described in the paper. Lastly Salamat Sharif et al. used optimisation results from only eleven networks spread across the year to derive a mean average power losses reduction. However, the fact that a well selected spread of optimised case studies are presented is favourable as it shows that the optimisation technique is robust against a range of network conditions. This differs with the other investigations by Bansal et al. [13], Bennett [18], Ramos et al. [77] and Karoui et al. [78], who only presented optimisation results on a single practical network or a small number of practical networks.

3.6 Development of SCORPF for Control Centre Use

Extensive literature on the subject of OPF dating back to the 1960s is available [80]. Rapid development of the subject took place in the 1970s leading to OPF techniques that utilise an LP based approach developed by Stott et al. [33, 40] and in the early 1980s using techniques developed by Irving and Sterling [81]. The late 1980s saw the development of a full SCORPF compact technique [34, 32]. The Combined Active and Reactive Dispatch algorithm (CARD), which was developed in the mid 1990s by Chebbo and Irving [15, 16], was described in chapter 1. The 1990s also saw the first control centre implementation of these techniques in practical tools, which considered a small number of contingencies

[17]. The last fifteen years has seen the development of many other optimisation approaches based on non-linear programming and heuristic approaches. Over time LP based optimisation approaches have been proven to be fast and robust, which are important characteristics when solving large-scale practical security-constrained power system optimisation problems [84]. LP based approaches have several other advantages including an ability to quickly determine if a problem is infeasible and to handle large numbers of power system operating limits. The main disadvantage of the LP technique is that it cannot find the global optimum solution to non-convex power system optimisation problems.

There is limited literature describing the actual implementation of SCORPF for aiding power system planning and operation. Issues with SCORPF still remain that need to be resolved before it can be used in practice, some of these issues will be described in section 3.7. This section provides a critique of the SCORPF studies that have been performed on the GB transmission system to reduce operational active power losses.

Bennett [18] conducted studies using Coldstart, which is based on the SCOPE program, to investigate the minimisation of active transmission losses, minimisation of reactive transmission losses and minimisation of generator reactive costs. Similar controls and constraints were specified to those described in section 3.5.1. Bennett used a voltage range of 1.00 – 1.04 for the 275 kV and 400 kV voltage levels. The SCORPF study carried out by Bennett only considered England and Wales and was secure against the 30 worst contingency cases. Table 3-3 shows two sets of results from Bennett [13]. Table 3-3(a) shows optimisation results performed using an offline network that is representative of 17th October 2004 at mid-day. Table 3-3 (b) shows results that are representative of a time corresponding to the 2004 winter peak demand. Nearly all of the optimisation results presented by Bennett show that the optimisation had the expected effect. However in the 2004 winter peak case, the reactive cost minimisation objective appears to have had a counter intuitive effect, because it has actually increased the value of the reactive costs. This result is an anomaly since the initial study was feasible, as it had been manually secured. A possible reason for this discrepancy

could be due to an inadequacy in the reactive costs minimisation objective that is described in chapter 6.

(a)

Study: Thursday Week 38 2004 Demand: 44219 MW, 19101 MVar			
Case	MVar Cost (£/hr)	Transmission Loss Cost (£/hr)	Total Cost (£/hr)
Base	14 104	19 371	33 475
Active Losses	19 186	19 307	38 493
Reactive Losses	18 552	19 221	37 773
Reactive Costs	13 094	19 328	32 422

(b)

Study: Winter Peak 2004 Demand: 59700 MW, 20173 MVar			
Case	MVar Cost (£/hr)	Transmission Loss Cost (£/hr)	Total Cost (£/hr)
Base	22 105	29 003	51 108
Active Losses	23 662	28 832	52 494
Reactive Losses	26 763	28 595	55 358
Reactive Costs	22 429	28 745	51 174

Table 3-3. Bennett [18] results obtained from different objective functions.

Bennett concluded from all four sets of results that the active losses minimisation objective reduced active transmission losses between 0.3% and 1.3%, but increased reactive costs by at best 1080% of the transmission loss savings. The reactive losses minimisation objective reduced active transmission losses between 0.2% and 1.4%, but increased reactive cost by at best 690% of the transmission loss savings. The reactive costs minimisation objective reduced active transmission losses by between -0.4% and 1.3%, and decreased reactive costs by up to 20%. Bennett therefore concluded that the reactive costs minimisation objective was the most economical objective, but noted that the solutions utilisation of dynamic reactive plant was impractical.

Bansal [13] also performed SCORPF studies using SCOPE. Bansal repeated some of Bennett's work using the single 17th October 2004 mid-day case, but expanded on the work by including 293 contingency cases.

Both investigations, by Bennett and by Bansal, determined that the reactive costs minimisation objective performed best overall. Nearly all the results in both studies showed that this objective reduced the cost of transmission losses, and also achieved the lowest overall costs. There was however a substantial differences between Bennett and Bansal's active losses minimisation results. As discussed above Bennett showed that this objective reduced the cost of transmission losses, but increased generator reactive power costs by over ten times the savings made. In contrast Bansal showed that this objective could reduce active transmission losses and reactive power costs simultaneously. Bansal suggests that this difference could be due to differences in the generator reactive power costs. Bennett assumed fixed reactive cost data, while Bansal considered varying reactive device cost data. This explanation does not appear to fully explain the discrepancy as most generators were paid at the default rate for reactive power generation or absorption [82]. An alternative explanation is that the observed discrepancy in their results was caused by differences in their usage of Coldstart and SCOPE.

Bennett and Bansal's results indicate that SCORPF has significant potential to securely reduce active transmission losses and reactive costs. However their work has revealed that the SCORPF technique must be robust and constraints must be included in the problem to ensure that it is realistic e.g. constraints on the amount of dynamic MVar reserve. Bennett has suggested that further work should include an investigation into multi-objective SCORPF that uses a combination of the reactive costs and active transmission losses objectives.

Another limitation of Bennett and Bansal's work is that it only investigated optimisation of the England and Wales controls and considered at most 293 contingency cases. ENCC Engineers routinely consider around 800 contingency cases – it is therefore important to include all of these cases in the optimisation to ensure system security.

Bennett and Bansal did not investigate the underlying SCORPF algorithm or tackle data modelling issues that may adversely affect the optimisation. The optimisation method utilised by Bennett and Bansal suffered from all of the issues

affecting Coldstart listed in section 3.4.4. This issue represents a significant limitation, as the underlying network model can be crucial in ensuring a well conditioned problem such that the SCORPF process is robust and the final solution is realistic [34]. Previous SCORPF tools at National Grid have applied a final stage of discrete variable rounding, this involved setting each discrete variable to its nearest physical value, however this was found to degrade optimality and produce final solution infeasibility.

3.7 Challenges to SCORPF

This section provides a brief overview of the challenges described in the literature that are faced by SCORPF technologies. To enable SCORPF technology to be of practical use in a control centre environment these limitations must be addressed. Section 3.7.1 examines the general limitations with existing SCORPF technologies, while section 3.7.2 examines specific limitations for solving the real-time SCORPF problem. Chapters 4 to 7 provide potential solutions to some of these limitations by presenting novel technologies backed up by comprehensive work confirming the improvement.

3.7.1 SCORPF technology limitations

Discrete devices

The SCORPF problem is discrete in nature. Most existing SCORPF tools treat all controls as continuous and then round each discrete control to the nearest discrete value. This procedure can sometimes be acceptable when the discrete step size is small, which is often the case for a transformer tap or phase-shifter angle. However for large shunt capacitors and reactors this round off can create violations and significant sub-optimality. Many recent publications [24, 25, 26, 27] have argued that the discrete shunt switching problem essentially remains unsolved in a reasonable time on a complex large-scale power system. Macfie et al. [21] proposes a novel shunt rounding technique that can be readily implemented to extend existing SCORPF software and demonstrates an improvement on the solution obtained using standard techniques.

Multi-objective weighting factors

The standard technique used to solve the multi-objective power system optimisation problem is to form a weighted sum combination of the individual objectives [29, 83]. This technique can only find all points on the Pareto Curve when the Pareto Curve is convex. Secondly it has been frequently observed that an even distribution of weights fails to produce an even distribution from all parts of the Pareto Curve [30]. The large-scale SCORPF problem is non-linear and therefore both of these phenomena are possible. These pitfalls would make a multi-objective optimisation control centre tool unreliable since it is impossible to know the correct weights needed to generate points evenly on a Pareto Curve without actually knowing the shape of the Pareto Curve in advance.

Contingency handling

Recent research has argued that reactive power planning should not only consider the base case power flow problem, but also contingency case power flow [84], which leads onto a practical requirement for SCORPF. Any practical SCORPF operation tool needs to consider all credible contingencies in order to achieve the same level of security as a manually secured network. However, there is a shortage of technical literature on the subject of SCORPF considering a large number of contingencies.

It is also important to note that a robust method for selecting credible contingencies on large-scale networks needs to be devised in order to ensure that the optimisation does not produce either an artificially expensive solution due to being over-secured or an impractical solution due to being under-secured.

Data modelling

The network data and parameters that form an SCORPF network model can be either static such as topology information or varying such as demand level. Credible contingencies need to be selected to ensure that the network is fully secure, and realistic constraint limits need to be applied. Poor data can lead to ill conditioning and problems converging, therefore a good data model is crucial to ensuring the accuracy and usefulness of the result [85]. Papalexopoulos [86] states that ‘Embedding the OPF solver in these models is a formidable task placing

onerous requirements in system modelling, data handling and methodology development’.

Ease of use and comprehensibility

One common experience among control engineers that use an SCORPF solver is that they cannot understand how a solution is arrived at, the SCORPF is acting like a ‘black box’. This was one of the problems with ACCORD [17]. The SCORPF tool therefore needs to be relatively transparent, as well as simple to use and flexible.

Non-convergence

Non-convergence due to the infeasibility of the SCORPF problem is common. Clear diagnostics, soft constraints and correct modelling of the SCORPF problem are required to understand and avoid the non-convergence problem [87]. Rapidly achieving convergence, identifying the causes of non-convergence, reliability and robustness are essential to ensure the success of any practical SCORPF tool. These features are the main advantages of an LP based optimisation method, such as the one that was described in chapter 2, over competing methods such as the non-linear programming method. Ultimately SCORPF must improve until the process is unconditionally robust.

Local minima

The mathematical solution to the large-scale SCORPF problem is challenging due to the large number of constraints that need to be considered in the problem. Based on the required objectives, controls and constraints the SCORPF problem can be formulated with discrete, continuous, non-linear and non-differentiable equations. Finding the global solution to this problem can be an NP-hard problem, which means that any solution found in a reasonable time will almost always be at a local minimum. In practice finding a solution that is cheaper than the best manual solution is good enough – it is more important that the optimisation solution is feasible. [84]

Equivalent network models

The network power flow models can include some external systems represented as a reduced equivalent. These power flow equivalents are used to reduce the size of the network or to model the unobserved systems. If SCORPF is performed on a model that includes reduced equivalents, using the transmission losses minimisation objective, then inaccuracies can occur. If the losses in the equivalent are small then a large portion of the power flow may be redirected through the equivalent. Some equivalent branches have a negative resistance, which would cause large inaccuracies in the SCORPF result. If the losses and inequality constraints on the equivalents do not need to be considered by the SCORPF then they should not cause a problem in the optimisation [88].

3.7.2 Real-time specific SCORPF technology limitations

Number of control changes

The solution from most SCORPF algorithms consists of a set of suggested control actions specified for all of the optimisable control variables. Such a solution would not be practical for any realistic implementation of real-time SCORPF, because it is not feasible to implement more than a few control actions at a time. This problem arises due to the limitation on the control engineer's time and device depreciation costs that result from excessive switching. It is not possible to simply select the most effective control actions from a given set, because all control changes need to be considered to ensure solution feasibility. [89]

A possible solution is to include a cost in the objective function proportional to the control change [89]. Depending on the magnitude of the assigned costs, the effect would be to reduce the number of control changes suggested by the optimisation. It is unclear how the magnitude of each cost should be assigned in order to limit the number of control changes effectively. Since this is a multi-objective optimisation with a linearly weighted objective function it will suffer from the same drawbacks described in section 3.7.1.

Uncertainty in data model

Real-time SCORPF is affected by the accuracy of the metering data that it uses, which can introduce an element of uncertainty into the optimisation. These issues are often overlooked in the SCORPF literature; therefore consideration needs to be given for methods to cope with this uncertainty. In the manual reactive dispatch process engineering judgement is often used to determine those meter readings that are reliable and those meter readings that should be ignored. El-Hawary and Mbamalu [90] presented a stochastic method of performing OPF for active power dispatch. The uncertainty in each variable was modelled using a normal distribution around the variables value. This technique has also been used more recently by Kimball and Clements [91].

The real-time SCORPF should use the state estimator (SE) solution values rather than the raw metered values. This is because the SE solution values are considered to be more reliable than the raw meter reading values, as the SE calculation process takes into account the following information:

- The network topology.
- Meter readings.
- The uncertainty in each meter reading.
- The physical power flow constraints.

SCORPF algorithm speed

The SCORPF algorithm can never run too quickly, particularly in real-time applications. In order to successfully meet the other challenges listed in this section it is inevitable that existing SCORPF technology will take a significant amount of time to determine an effective solution. Therefore improvements in performance will need to be made, however the SCORPF process is always going to take a finite amount of time to arrive at a solution. Past experience with optimisation tools in practical use at National Grid has suggested that a maximum execution time of ten minutes is reasonable.

Time linked SCORPF

Extensive literature exists on the ORPF static snap-shot problem, but only limited literature exists on ORPF problems that consider the time-domain aspects of the problem [92, 93, 94, 95]. In other words most ORPF studies determine an optimal solution that is only valid for a specific generation and demand condition. It is possible that the optimised feasible solution for one set of network conditions is not optimal or/and feasible for another set of network conditions. Taylor et al. [95] has suggested that a time linked ORPF approach should be used, which solves the ORPF problem at specific points in the daily demand cycle. Bie et al. [96] split the daily demand cycle into time intervals, within each time interval discrete variables were held constant; it was assumed that continuous variables could be modified throughout the time period. The time interval was then split into sub-intervals in which the continuous variables were held constant. Future work now needs to be performed to apply dynamic constraints to the full SCORPF problem in order to ensure that the solution is valid at the present network condition and at anticipated future network conditions.

Study mode, closed loop mode and the user interface

Real-time SCORPF programs can be implemented in either a study mode or a closed loop mode. In study mode SCORPF periodically updates a list of suggested control changes that will minimise an objective function such as costs or active transmission losses. The study mode relies on control engineers to implement all the suggestions, however due to time constraints this may not always be achievable. It is desirable to minimise the number of control changes when operating in study mode, which was an issue described at the beginning of section 3.7.2. It is also important to have a clear user interface that gives control engineer enough flexibility to setup the optimisation, while remaining simple and robust. The output from the tool must be in a meaningful form that the engineers can readily implement.

In closed loop mode the control changes determined by SCORPF are implemented automatically onto the power system. This would require an interface directly with the IEMS. Papalexopoulos [86] indicates that a major problem with closed loop SCORPF is the integration with other online functions

that are executed with different periodicities, such as economic dispatch and contingency analysis. These interface concerns along with the system modelling, data handling and methodology requirements will need to be addressed before a robust and reliable close loop SCORPF can be implemented as a control centre system. Only after solving these problems, and after an initial evaluation period in a study mode, will control engineers gain trust in the real-time SCORPF tool to confidently allow it to run in an unattended closed loop mode.

3.8 Summary

This chapter has presented the commercial, environmental and technical background information that is relevant to the operational losses minimisation optimisation of the GB transmission network. A detailed description of operational active transmission losses has been presented, which included information on how customer metering is adjusted to account for losses and how National Grid is incentivised to minimise operational costs. Chapters 4 to 7 of this thesis will focus on the development of SCORPF tools and techniques for minimising operational transmission losses and reactive costs by adjusting the voltage profile of the transmission system. A firm understanding of existing operational reactive power control practices has been established in this chapter, which will form a fundamental base of knowledge crucial to developing SCORPF techniques relevant to the industry. Finally this chapter presented a literature review describing the current limitations of SCORPF and the issues affecting previous practical implementations of the technology in the UK and in other countries.

Chapter 4

Practical SCORPF applied to Large-Scale GB Transmission Network Models

4.1 Introduction

National Grid has a commitment to maintain a safe, secure and economical electricity transmission network in England, Wales and Scotland, which is established under the terms of its Transmission License agreement [97]. At present the dispatch of available reactive controls is achieved by a manually intensive adjustment process. Previous studies have shown that optimisation of the network settings may offer several operational benefits. Studies by Dandachi [17], Bennett [18] and Bansal et al. [13] demonstrated how optimisation techniques can be applied successfully to solve problems involving the GB transmission network to reduce operational costs. This chapter presents results from recent SCORPF research [19, 20, 22, 23] that builds upon the findings previously presented in the literature. The results and analysis presented in this chapter quantify the benefit that can be achieved from solving the SCORPF problem when one is considering the full England, Wales and Scotland transmission network model secured against 800 credible contingency cases to reduce operational active transmission losses. All optimised studies complied with the Security and Quality of Supply Standards (SQSS) [3], which set out the minimum requirements for the secure planning and operation of the GB transmission system. These standards include definitions of acceptable voltage conditions during normal operation and following $n - D$ contingencies, where the D refers to the loss of a double circuit.

This chapter begins by reviewing the relevant security standards that National Grid is required to maintain and then describes the SCORPF formulation and optimisation processes that were utilised in this research. The remaining sections

of this chapter present detailed SCORPF results obtained using the active transmission losses minimisation objective. Finally the practical significance of these results will be established.

4.2 Operational Procedure and Security Standards

The Transmission Requirements (TR) department at National Grid takes responsibility for planning the secure operation of the network. This planning process involves the preparation of detailed operational plans from around 13 weeks ahead of real-time, and includes the manual secure adjustment of the network's voltage profile taking into account all planned outages due to maintenance and construction work on the transmission system [13]. Secure day-ahead peak demand low-loss network studies are prepared by TR. These studies are then transferred to the control centre where these studies are fine tuned by the Transmission Analysis Engineer (TAE) for each day; this involves the adjustment of demand, generation and the outage pattern to match the expected situation at real time. Within the ENCC, National Grid bases its target voltage profile on the voltage profile in the plans produced by the TAE. Finally the Transmission Dispatch Engineers (TDE) manually issues control instructions to achieve a secure and economical voltage profile. It is envisioned by the author that SCORPF process could be designed to improve each of these operational planning and dispatch stages such that the maximum benefit is achieved.

As system operator, National Grid must comply with its Transmission Licence requirements [97], one of which is to meet the SQSS standards [3]. Within this research reactive controls are adjusted using an SCORPF algorithm that is constrained by the regulatory voltage requirements specified in the SQSS. It is essential to ensure that available dynamic reactive reserves are maintained on SVCs and generators in order to secure the post-fault system voltages in the event of the most onerous credible fault. The steady state voltage condition must be secured both pre and post fault as summarised in Figure 4-1. At customer connections, the voltage must not change by more than the indicated limits in the event of either a single circuit (SC) or double circuit (DC) outage.

Annually the industry regulator, which is the Office of Gas and Electricity Markets (Ofgem), and National Grid agree an incentive scheme that aims to encourage the cost effective operation of the network such that overall Balancing Service costs are minimised. The scheme that was described in section 3.2.4 includes a transmission losses cost and generator reactive utilisation cost component [13]. Since the precise details of this scheme will vary from year to year it is impossible to determine the magnitude of the incentive scheme profit that might be achieved from implementing an SCORPF process in practice. It is usual practice for National Grid to quote the raw reduction in Balancing Service costs rather than the net incentive scheme profit or loss when assessing the benefit of implementing an improvement in its operational practice.

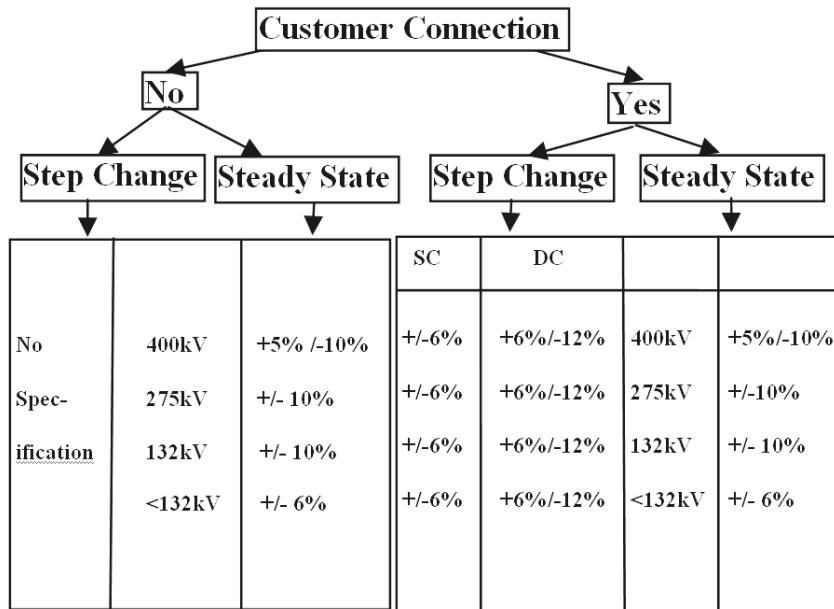


Figure 4-1. Acceptable steady state voltage and voltage step change conditions on the GB transmission system [3].

4.3 SCORPF Formulation

4.3.1 Objective function, constraint equations and control variables

The research described in this chapter utilises the active transmission losses minimisation objective function, whose value is given by the following formula [52]:

$$Losses_{Tot}^{AC} = \sum_{L=1}^{n_L} G_{ik} (V_i^2 + V_k^2 - 2V_i V_k \cos \theta_{ik}) \quad (4-2)$$

L is a line with conductance G connecting the i th node to the k th node, and n_L is the total number of lines on the network. V and θ refer to the nodal voltage magnitude and angle.

In SCORPF the generalised scalar objective to minimise is given by:

$$f(U^0, X^0) \quad (4-1)$$

U is a set of the control variables and X is a set of dependent variables. The superscript 0 indicates that the variable refers to the pre-contingency power system.

The OPF is bound by equality and inequality constraints [17]: The equality constraints are given by the pre and post contingency power flow equations, where superscript c refers to the c 'th contingency case:

$$g^c(U^c, X^c) = 0 \quad c=0, 1 \dots n \quad (4-3)$$

Equipment control limits are represented by the following hard inequality constraints:

$$U_{MIN}^c \leq U^c \leq U_{MAX}^c \quad (4-4)$$

Hard/soft constraints on voltage limits and voltage changes limits are represented by:

$$X_{MIN}^c \leq X^c \leq X_{MAX}^c \quad (4-5)$$

Other hard/soft constraints such as reactive reserve limits can be represented by:

$$h^c(U^c, X^c) \leq 0 \quad c=0, 1 \dots n \quad (4-6)$$

The modelled intact network case and contingency case constraints within the SCORPF included:

- Control limits (e.g. generators and SVCs).
- Bus voltage limits.
- Voltage change limits.
- Generator MVar reserves – relaxed for contingency cases.

When contingencies are included in the optimisation the resulting reactive generation pattern should by definition have adequate MVar reserves, this will ensure that the post contingency voltage profile is secure. The inclusion of a large number of contingencies should imply widespread MVar reserves, which would make the need to define reserve constraints redundant [71]. MVar reserve constraints are however included for the following reasons:

- To prevent voltages from being pushed to their limits.
- To allow for error in the network data.

The modelled control variables within the SCORPF included:

- Continuously variable high voltage side generator voltage targets.
- Continuously variable Static VAR Compensator (SVC) voltage set-points.
- Discrete shunt capacitors on/off
- Discrete shunt reactors on/off.

The voltage target at the high voltage side of each generator transformer was maintained by tapping the corresponding generator transformer, which affected the amount of reactive power output required from the attached generator. High voltage busbar controls were only flagged as optimisable if they met a special custom designed criteria, which was based on the sum of the attached reactive capability. The voltage control was flagged as optimisable only if its total reactive capability was amongst the 50 voltage controls with the largest attached reactive capability.

This issue required consideration because the inclusion of voltage target controls with inadequate reactive generation was found to cause SCORPF convergence problems [21].

4.3.2 Contingency case constraints

Each contingency case that was included in the SCORPF added thousands of constraints to the problem. Typically the SCORPF considered around 800 contingency cases and therefore the total number of SCORPF constraints ran into the low millions [34]. The contingency list included credible cases that were reflective of the England, Wales and Scottish transmission network in order to

ensure that the post-BETTA (British Electricity Trading and Transmission Arrangements) operational requirements were satisfied. The studies carried out by Bansal et al. [13] and Bennett [18] only considered the pre-BETTA operational requirements, which did not include operational constraints for the Scottish transmission network, and therefore used a shorter contingency list. National Grid Planning Engineers have a pre-defined list of credible contingency cases, and therefore the same list was used to define the credible contingency cases in the SCORPF research performed within this project. Contingencies had been chosen on the basis of engineering experience and judgement relating to specific voltage issues that can occur in a locality. Each contingency was modelled so that it represented the state of the system at a time phase at least three minutes after a fault had occurred on the system, when all automatic action was assumed to have already taken place. To encode each contingency, appropriate protection schedules were consulted and limitations of the offline model were considered. Typically each single circuit contingency was represented by multiple elements in the model up to the relevant circuit breaker. The contingency power flow was modelled in a steady-state condition where loads were assumed to be voltage independent and transformers were allowed to vary their tap position.

4.3.3 Optimisation process

The SCORPF process, which is based on a Sequential Linear Programming (SLP) technique, is shown in Figure 4-2 [34, 40]. The first stage of the SCORPF process involved achieving a converged Newton-Raphson AC power flow on the intact network and on each of the contingency case networks. In contingency power flow only automatic controls were allowed to move during a fault condition, which meant fixing the post-fault generator transformer tap positions. In the research presented in this chapter all credible contingencies, as selected by National Grid Planning Engineers, were modelled within the SCORPF process. The research presented here thereby extends on previous SCORPF research using GB transmission network models that only considered a smaller number of contingency cases [17].

The central algorithm of the SCORPF is an LP with control variables formulated in a compact form, as explained in section 2.2. The optimisation warm starts from

a sub-optimal but feasible point. The optimisation process tends to make large control changes during the first few iterations, which can cause constraints to become violated. The LP process then enforces these violating constraints and updates the optimisable control dispatch in order to move the operating point back to feasibility.

The SCORPF process maintains a list of critical contingency cases i.e. those cases with binding or near-binding constraint limits. This list is updated at intervals during the SCORPF process by running contingency analysis to identify the critical contingency cases that should be added to or removed from the critical contingency list [32]. At each iteration of the SCORPF the central LP algorithm tries to enforce all binding constraints that are present in the intact network and each of the critical contingency case networks. The SCORPF process is pronounced converged when the optimised control movements are within a user-defined tolerance and all constraint violations have been alleviated.

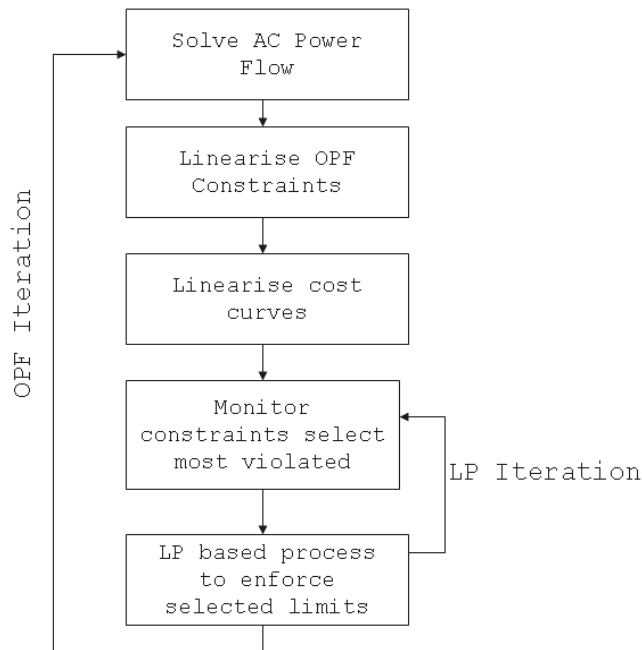


Figure 4-2. SCORPF process. Sourced from [32].

4.4 Offline SCORPF

4.4.1 Model formulation

This section presents results that were acquired using weekday and weekend day-ahead offline network studies representative of the network during the year of

2007. Each of these studies had been manually optimised by TR engineers to represent a snapshot in time corresponding to a daily demand peak occurring around mid-day. The investigation to determine the potential for SCORPF to reduce costs and losses proceeded in a series of four stages. The initial stage of the investigation proceeded by selecting transmission network studies representative of network conditions over an even distribution of days across the year.

The second stage of the investigation involved developing an accurate method to formulate each SCORPF model, so that it correctly represented the corresponding offline model. This involved ensuring that the control models for generators, transformers, lines, busbars, SVCs, shunt capacitors, shunt reactors, loads and network gain were accurate such that the Newton-Raphson power flow solution results from the SCORPF engine agreed with National Grid's in-house power analysis software that is called ELLA. Power flow solution results needed to be aligned for the intact network case and for each of the modelled contingency cases. Discrepancies between the results were addressed using the original procedure that is presented in Figure 4-3. This procedure consisted of the following steps:

1. Use the best available SCORPF formulation method to create an SCORPF model from the corresponding offline ELLA study.
2. Run power flow using the SCORPF engine on the SCORPF model that was formulated in the previous step and also run power flow using ELLA on the original ELLA offline study.
3. Identify any disagreements between the two sets of power flow results. For example there could be a difference in the total active losses. If there is no disagreement then stop.
4. Trace through the SCORPF model and ELLA model to identify the source of the disagreement. For example this could involve comparing the reactive power flow across lines and then determining where the difference gets bigger.
5. From these results try to identify the root cause of the disagreement.
6. Make manual corrections to the SCORPF model. If this doesn't improve the agreement go back to step 3.

7. Create an update to the SCORPF formulation process, so that the problem is corrected at all locations on the network.
8. Repeat this procedure from step 1.

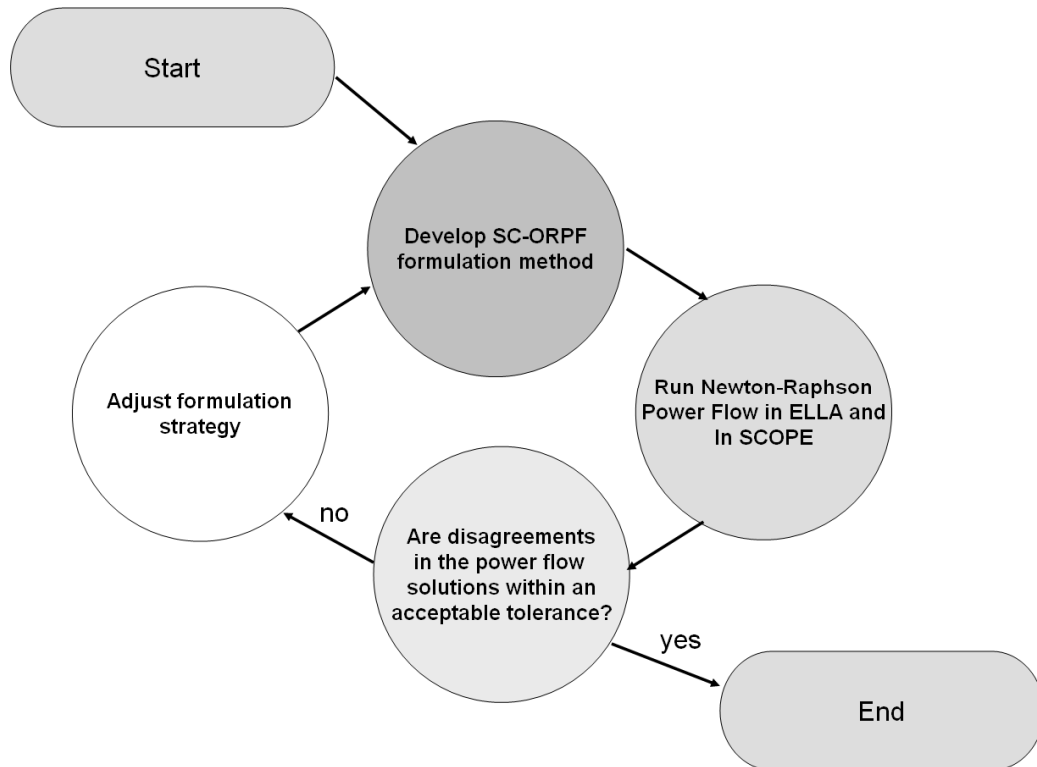


Figure 4-3. Process for achieving agreement between the ELLA and SCORPF power flow solutions.

The third stage of the investigation involved adding appropriate optimisation data to the SCORPF model. This involved determining and flagging appropriate optimisable generator voltage target controls. This stage also included incorporating optimisable shunt capacitor and shunt reactor controls into the optimisation. This involved recognising the shunt controls that were available in the baseline data and flagging them as optimisable if they were eligible for switching. A number of shunts were included as fixed blocks of susceptance in order to model the equivalent network gain from the low voltage network.

The voltage limit on busbars was defined to a standard that was stricter than that shown in Figure 4-1 [3]. A stricter standard was required in order for the SCORPF solutions to be consistent with existing operational practice. Different standards were applied pre and post fault. The voltage ranges were defined as:

- 125kV to 139kV - for the 132kV pre-fault and post-fault network.
- 261kV to 289kV - for the 275kV pre-fault and post-fault network.
- 390kV to 416kV - for the 400kV pre-fault network, note that a maximum upper limit of 440kV was applied post-fault.

It is National Grid practice to apply a pre-fault 416kV upper limit, as opposed to a 420kV upper limit, in order to account for an assumed 1% uncertainty in the metering.

The size of the voltage change at each busbar between the intact network case and each modelled contingency case was also constrained to within the requirements defined in the SQSS [3], see Figure 4-1.

The fourth stage of the investigation was the SCORPF itself. This stage included evaluation of the network losses, generator reactive utilisation volume, reactive gain and violations at the beginning and at the end of the SCORPF. The active losses were calculated as the sum of the active losses on each branch in the network, given by equation 4-2. The generator reactive utilisation volume was calculated by summing the absolute value of the reactive output from each generator. The reactive gain was calculated by summing the shunt gain BV^2 minus the series reactive losses I^2X across all network components. The number of voltage violations was determined by summing the number of busbars in the intact network and each contingency case that had a voltage outside the defined limit. The presents of voltage change, transformer tap, reserve and reactive generator limit violations was also detected and recorded. The SCORPF problem was solved using the SCOPE engine [39] version 12.0. The solution process is shown in Figure 4-2.

4.4.2 Initial SCORPF results

Figure 4-4 shows results obtained with the investigative method described in section 4.4.1 using the active transmission losses minimisation objective. The results were obtained from 12 offline network studies spaced at monthly intervals representative of different Tuesdays across the year of 2007. Tuesday was chosen

because it tends to exhibit the largest demand amongst all of the weekdays. SCORPF managed to achieve a consistent reduction in active losses on each of the networks that were tested, the average reduction was 1.35%. The reduction in active losses is accompanied by an increase in the network gain, which occurs because the optimisation is reducing the active losses by raising the voltage profile. Interestingly these results also show that a reduction in generator reactive utilisation occurred when applying the active transmission losses minimisation objective. A possible explanation for this is that the initial network is sub-optimal in terms of both the active losses and the generator reactive utilisation, thus allowing the active transmission losses minimisation objective to produce a reduction in generator reactive utilisation.

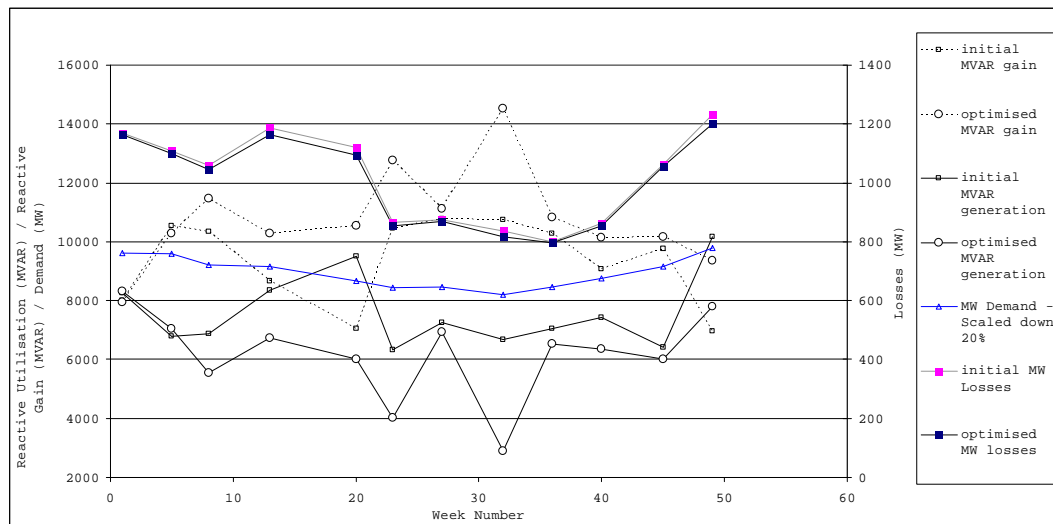


Figure 4-4. SCORPF results showing a comparison of active losses, reactive gain and reactive utilisation during 2007.

4.4.3 Boundary flow results

Constraint boundaries on the transmission network have been defined by National Grid as limits on the power flow from one area to another area of the network arising from thermal, voltage or stability issues [98]. Figure 4-5 shows some of the major constraint boundaries on the National Grid Transmission System. The investigation presented in section 4.4.2 has been extended to consider these constraint boundary flows.

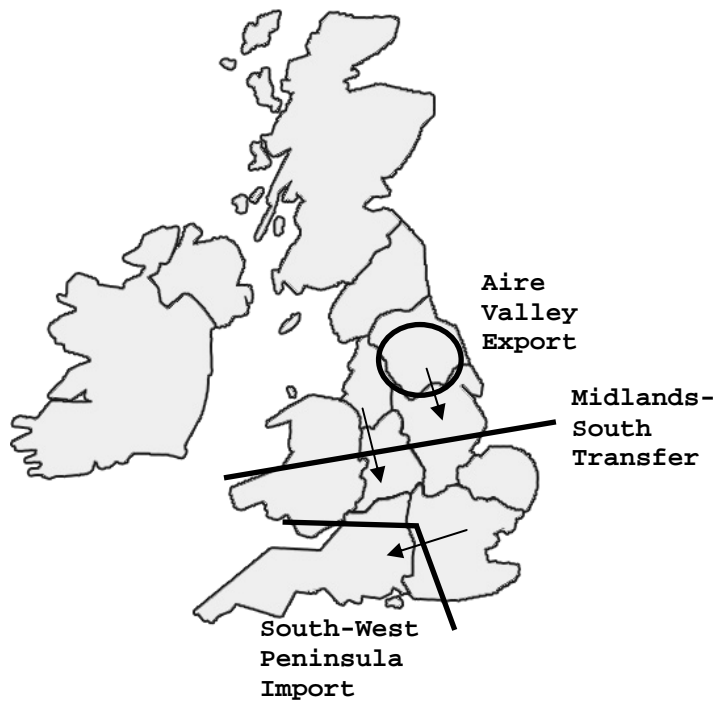


Figure 4-5. Constraint boundaries on the National Grid Transmission System. [98]

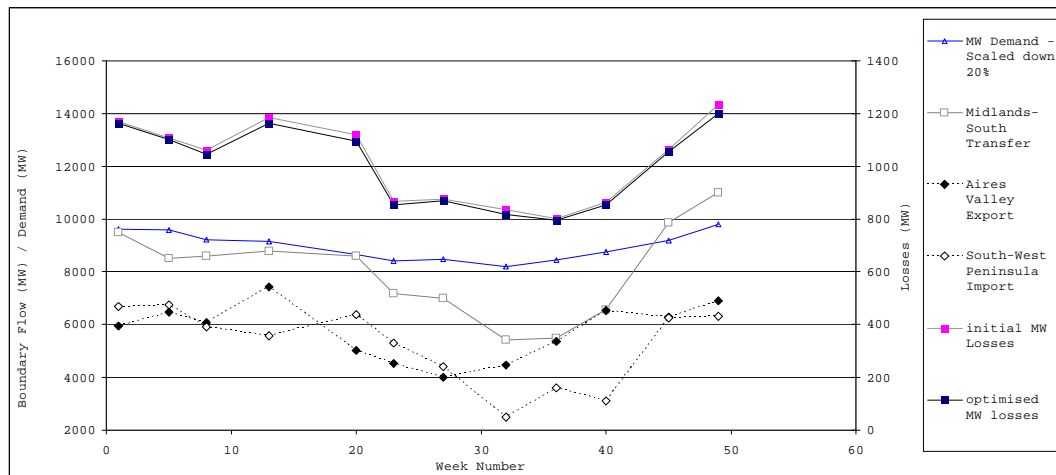


Figure 4-6. Boundary flows with an overlay of SCORPF results for the 12 networks presented in Figure 4-4.

Figure 4-6 shows the flow across constraint boundaries for the 12 networks spaced at monthly intervals. The results seem to indicate a correlation between the Midlands-South Transfer and the active losses on the network. This is consistent with expectation, because it is well known that large north to south flow corresponds to increasing active losses. These results do not reveal a correlation between the boundary flow and the amount of active losses reduction achieved by the SCORPF.

4.4.4 Sensitivity of active losses reduction to the number of shunt switching actions

Figure 4-7 shows how the level of active losses reduction is correlated with the number of shunt capacitors and shunt reactors that have flipped position during the optimisation. The slope and intercept of a best-fit line through the data points has been determined using linear regression. The R-squared value of the best-fit line is shown in the figure. This R-squared value corresponds to the total square error between each data point and the best-fit line. An R-squared value of one would correspond to a perfect correlation with linear behaviour, while zero would correspond to no correlation.

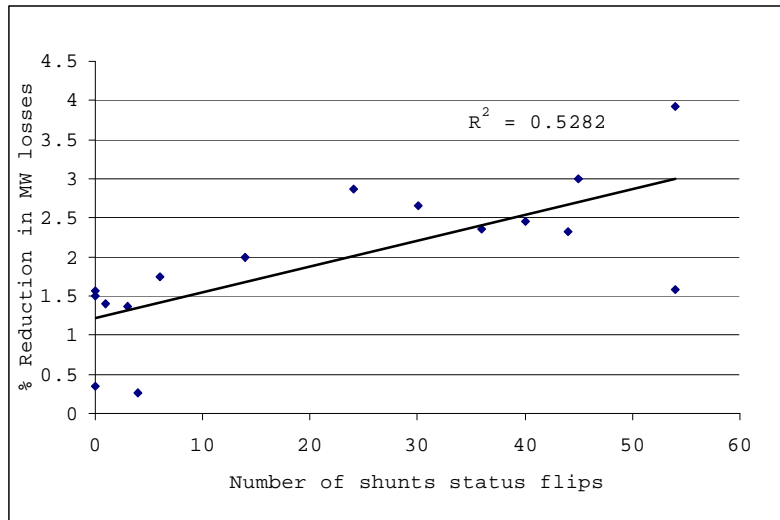


Figure 4-7. SCORPF reduction in active losses against the number of shunt status flips.

Figure 4-7 indicates that there is some correlation between the active losses reduction and the number of shunt status flips, this correlation has an R-squared value of 0.53. This relationship confirms the operational voltage control philosophy that an appropriate shunt switching configuration is important for achieving an optimal voltage profile. The average reduction in losses shown in Figure 4-7 is different to the average reduction in losses shown in Figure 4-4 since different network data was included in the investigation.

4.4.5 Sensitivity of generator reactive utilisation to active losses reduction

Figure 4-8 shows the results of Figure 4-4 re-plotted to show how the active losses reduction correlates with the generator reactive utilisation reduction. These results indicate a correlation between the intentional percentage reduction in losses and the un-intentional percentage reduction in generator reactive utilisation, with an R-squared value of 0.63. Therefore when SCORPF is executed using the active transmission losses minimisation objective there is usually a corresponding reduction in generator reactive utilisation in these study cases. The –ve values in Figure 4-8 indicate that occasionally the losses minimisation objective can cause the total reactive utilisation to increase.

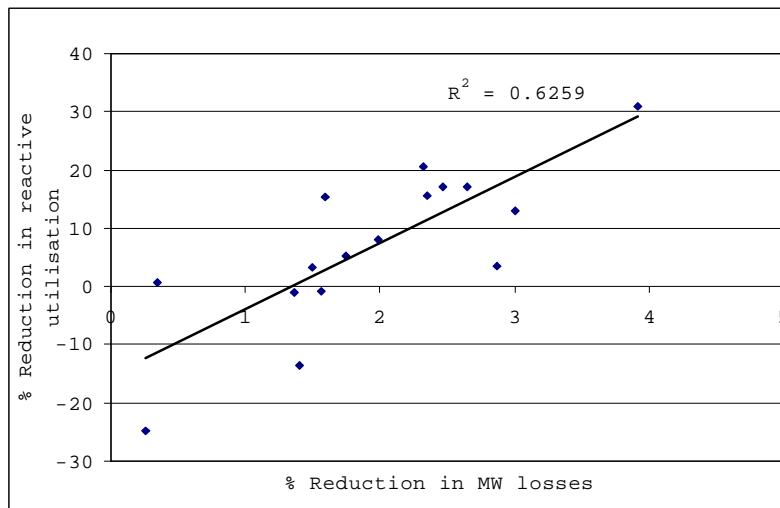


Figure 4-8. SCORPF reduction in reactive utilisation versus the reduction in active losses.

4.4.6 Voltage limit range results

Figure 4-9 shows SCORPF results derived from a single network study that is representative of a Tuesday in engineering week one of 2007. The figure indicates how the absolute value of the optimised active losses vary as the constraint limit range on the 400kV voltage is expanded. The voltage constraint limit range for the left most point on the figure has a range of 0.90-1.03 and the voltage constraint limit range for the right most point has a range of 0.90-1.05.

Figure 4-9 reveals that the active losses minimisation objective value gets smaller as the constraint range is expanded. This would be expected because the optimisation has a greater amount of freedom as the constraint range is expanded

and can therefore find lower loss solutions. Since we are raising the upper limit on the 400kV voltage constraint range it seems reasonable that the optimisation is finding solutions that have a higher voltage and therefore by Ohm's law incur lower losses. The figure also shows results from SCORPF when all controls are assumed continuous, and results from SCORPF when discrete controls are rounded to their nearest discrete value. Both sets of results appear to have a similar relationship with the voltage constraint range. It is also important to note that the continuous SCORPF result has generally managed to achieve lower loss solutions. It therefore appears that the process of rounding causes the optimised solution to become more costly. A novel technique will be presented in Chapter 5 to reduce the sub-optimality when discrete controls are included in the SCORPF.

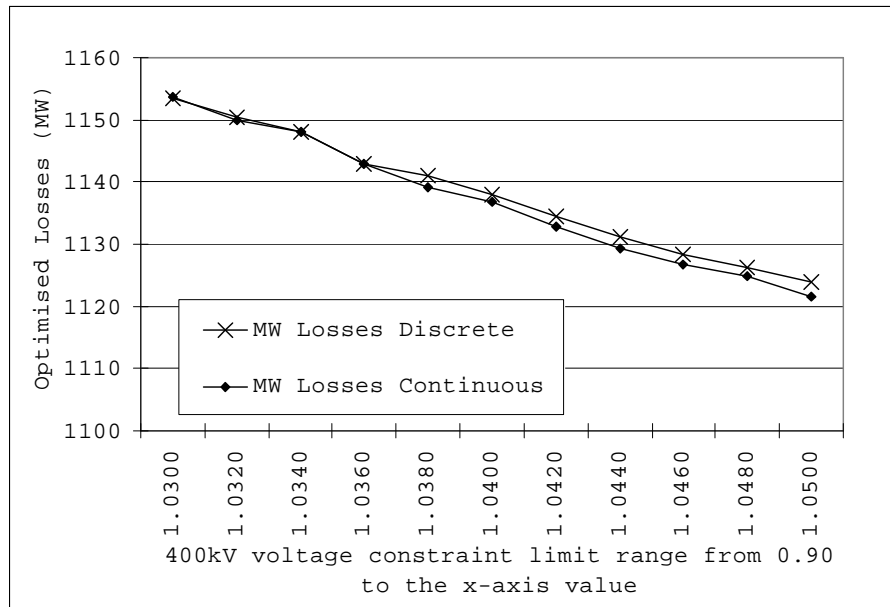


Figure 4-9. SCORPF active losses reduction result against an expanding 400kV voltage constraint range.

4.4.7 Variation in the SCORPF losses reduction result as the number of optimisable shunt controls is reduced

Figure 4-10 shows how the final optimised value of the active losses vary as the number of optimisable shunt controls is reduced from 260 to 0. The losses reduction generally deteriorates as the number of optimisable shunt controls is reduced. This relationship is to be expected because the degrees of freedom that the optimisation has available to achieve an improvement in the objective function gradually reduces as the number of optimisable shunt controls is reduced. When 260 shunt controls are included in the SCORPF the results indicate that there is a

significant difference between the SCORPF result with rounding and the SCORPF result where all controls are assumed continuous. This result demonstrates that rounding the discrete controls may introduce sub-optimality into the solution.

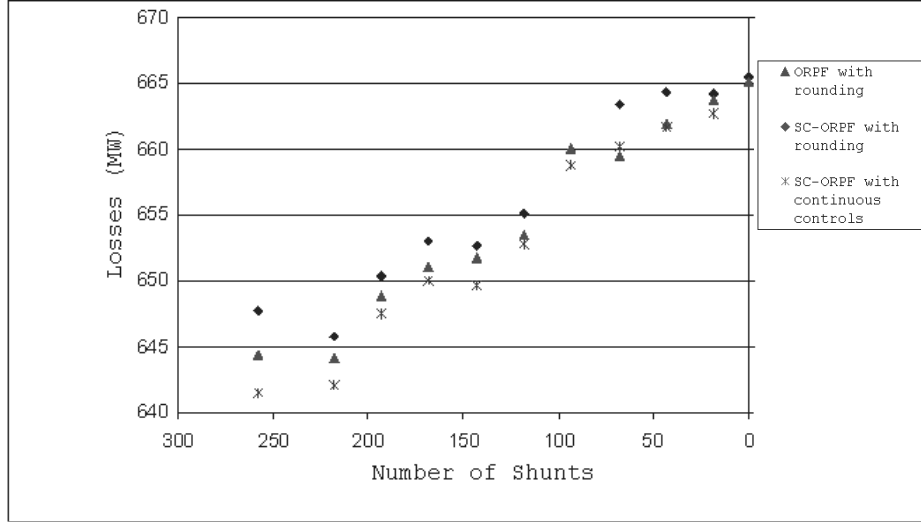


Figure 4-10. Variation in the optimised active losses as the number of optimisable shunt controls is reduced from 260 to 0.

4.5 SCORPF Multi-Stage Optimisation

4.5.1 Introduction to multi-stage optimisation

Analysis of the SCORPF solutions previously reported by Macfie et al. [23] revealed that voltages at some busbars were outside their designed constraint limits. The reason for these limit violations was found to be due to the rounding of the discrete control variables. These discrete variables were being assumed continuous during the main SCORPF process and only at the end of the final iteration were they rounded to their nearest discrete value. For example a 60 MVar shunt capacitor that had a continuous SCORPF solution of 29.22MVar would be set out of service upon rounding. Rounding in this case could cause sub-optimality. The discretization was also found to cause the system operating point to move outside of the feasible region resulting in voltage violations. It is sometimes possible that the discretization process may produce a solution with a smaller objective function value than the global optimal value, but will not be feasible. Alsac et al. [32] revealed that the SCORPF optimisation problem maybe sensitive to the starting point. To investigate both the discretization sub-

optimality and starting point sensitivity four different SCORPF approaches have been described and compared in this section.

4.5.2 Multi-stage approach

Four different SCORPF approaches are described below. The first three approaches provide solutions that can be physically implemented on the network, while the fourth approach is non-physical and is included for comparison purposes.

One stage optimisation – A single pass of SCORPF is performed. All controls are assumed continuous within the optimisation. At the end of the optimisation discretization takes place for discrete controls and a final power flow is then performed. The final solution may include violations due to the discretization process.

Two stage optimisation – Two passes of SCORPF are performed. The first pass is equivalent to the ‘One stage optimisation’ and the second pass is an SCORPF with only continuous controls with all discrete controls remaining fixed. The second pass should usually be able to secure violated limits created by the discretization.

Three stage optimisation – This novel approach includes three optimisation passes. The first stage is an initial pass of base-case only OPF that ignores contingency constraints. It is this first stage that tends to increase the amount of losses reduction achieved by the overall process, as it improves the starting point for the remainder of the optimisation. The ‘Two stage optimisation’ is then performed that executes the optimisation with all controls (both discrete and continuous) assuming all controls can be treated as continuous, all credible contingency case constraints are now included. The discrete controls in the solution are then rounded to their nearest discrete value and continuous controls are then used to remove any remaining violations. The final solution from the three stage optimisation tends to have lower cost and is usually violation free.

Continuous – A single pass of SCORPF with all controls assumed continuous. The final solution should be fully secured. The solution from this is not physical, since the discrete control limits will not necessarily be honoured.

4.5.3 Methodology

Five offline GB network studies that had been prepared by TR are considered in this section. Four 2008 day-ahead peak of the day studies were selected from examples used in the annual seven year statement [6] and an additional summer 1B night network was also chosen. This night time network was based on an ENCC Transmission Analysis Engineer's (TAE) study that had been set-up to represent a snapshot in time representative of the lowest point in demand. Table 4-1 presents parameters describing the five networks that were investigated in this section.

Name of network	Demand (MW)	Number of buses	No. of optimised voltage control buses	No. of discrete control variables	No. of individual generators	No. of inequality reserve constraints
Typical Winter	56023	3586	87	269	284	250
Winter Maximum	59287	3587	92	270	300	264
Summer Minimum	42234	3457	72	263	219	204
Typical Summer	42929	3465	73	263	223	213
Summer 1B Night	24824	3526	65	267	183	171

Table 4-1. Parameters describing networks that were investigated in this section.

SCORPF was performed on the five networks studies in Table 4-1 using each of the approaches that were described in section 4.5.2. The active transmission losses minimisation objective function was utilised in these investigations with the same controls and constraints described in section 4.3.1. The reduction in active losses as well as the number of final voltage violations in the optimised solution was recorded. In addition the number of contingency cases that became critical during the SCORPF was also recorded. A critical contingency case is one in which at least one of its constraints needed to be enforced within the LP at any stage during the SCORPF.

Analysis was carried out on both the initial un-optimised and the final optimised network studies to quantify how the SCORPF affected voltage stability. This analysis was performed in order to ensure that the SCORPF process was not compromising the voltage stability margin of the network.

4.5.4 SCORPF results obtained with the multi-stage approach

Figure 4-11 presents results showing that the main advantage of utilising a two or three stage SCORPF approach over a one stage approach is that all voltage limits are secured for. In four out of five of the cases the three stage SCORPF process managed to achieve the biggest loss reduction in a physical solution. Therefore these results indicate that the use of a preliminary ORPF stage can provide an additional reduction in the active losses. In the typical winter case, the 3 stage SCORPF approach achieved the worst improvement in the losses compared to the other approaches that were investigated, this is because the intact network initialisation stage may have caused additional contingency case constraints to become binding.

Generally the continuous SCORPF solution managed to find the lowest value of active losses, but the solution was non-physical because some discrete controls were set to values that could not implemented in practice.

The results shown in Figure 4-12 and Table 4-2 show more detailed SCORPF results from the two stage SCORPF technique. These results indicate that significant loss reduction has been achieved with a simultaneous increase in the lagging reactive reserve on generators. This seems to have been achieved as a consequence of the active losses minimisation objective, which is generally increasing the networks voltage profile such that the network gain is supplying reactive power to balance the reactive demand. Table 4-2 shows two values in the critical contingencies column indicating the number of contingencies that became binding during the first stage and second stage of the optimisation. There was only one case that had more than one critical contingency. This suggests that the active losses minimisation objective applied to these production network studies usually encounters a very small number of binding contingencies when warm starting from an initially secure point. This factor is important in ensuring that the SCORPF computation time remains short. Typically the SCORPF took around three minutes to complete.

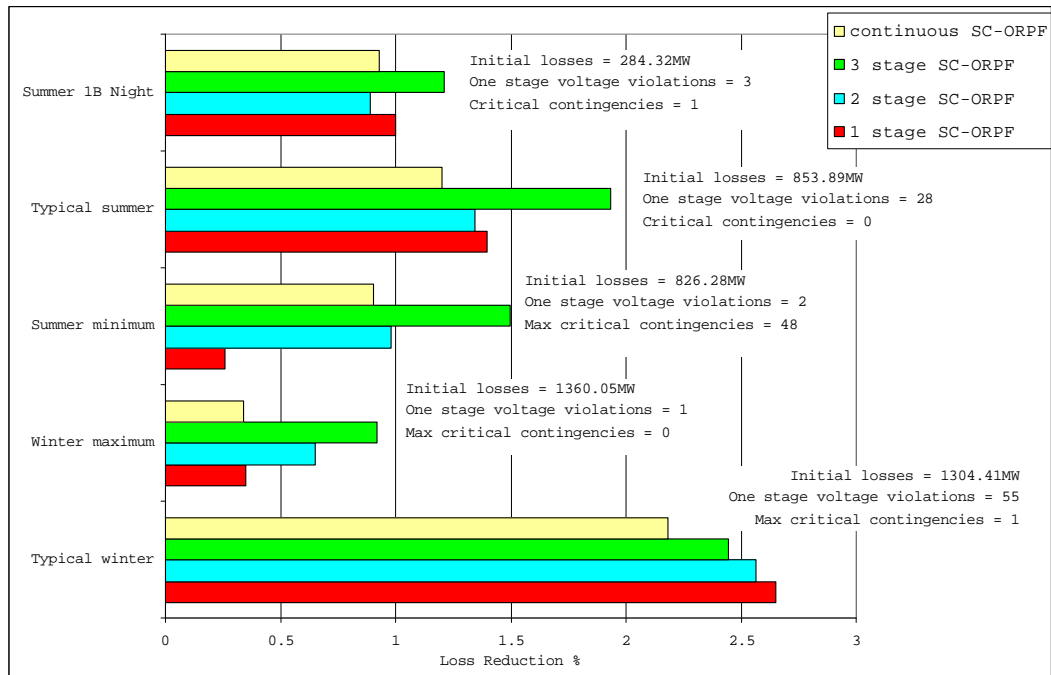


Figure 4-11. Active losses reduction for the five networks shown in Table 4-1.

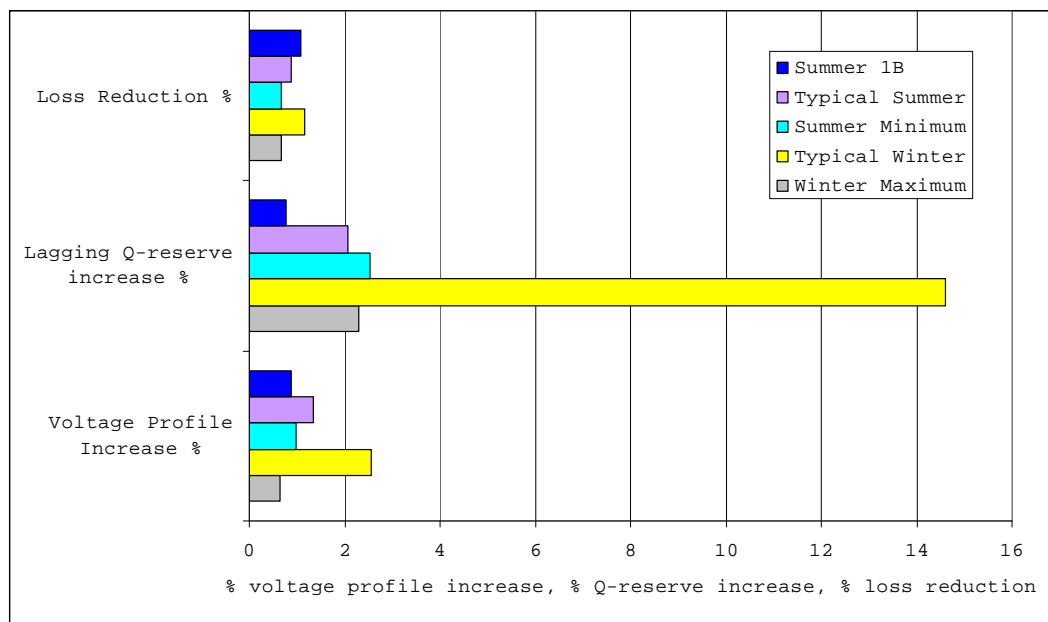


Figure 4-12. An alternative presentation of the two stage SCORPF results.

	Critical contingencies	Generator HV-side voltage changes	Shunts switched	Total shunt MVAR switched	Reactive Volume Change (%)
Winter maximum	0,0	88	0	0	-1
Typical winter	0,1	83	27	1721	-17.1
Summer minimum	48,1	71	4	160	10.2
Typical summer	0,1	72	1	-15	13.5
Summer 1B	1,1	68	0	0	4.8

Table 4-2. Solution details for the Figure 4-12 results, the critical contingencies column is explained in the text above.

4.5.5 Voltage stability margin results

Figure 4-13 shows results from a voltage stability analysis assessment that was performed on the winter maximum network listed in Table 4-1. These results show how the average voltages on the 275kV and 400kV busbars vary as demand is scaled up in value. From Figure 4-13 it can be seen that a system wide blackout of the optimised network would occur at a greater demand multiple than on the initial network. These results increase confidence that the voltage security of the optimised networks is at least as good as the initial network.

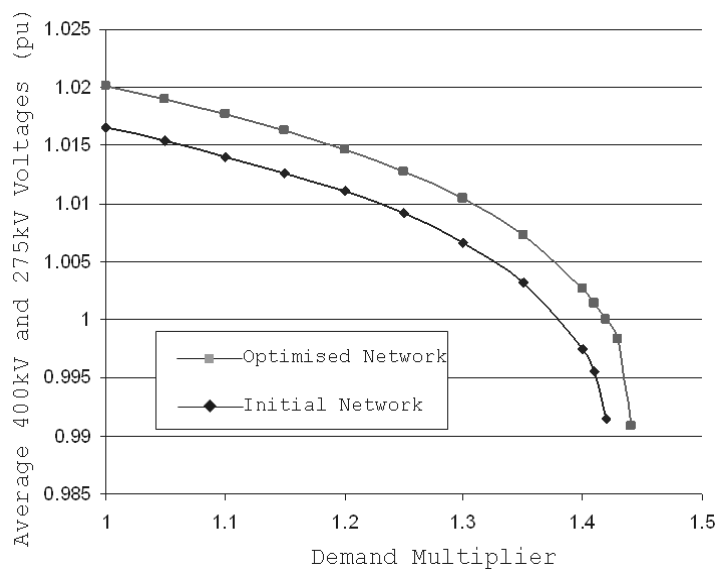


Figure 4-13. Voltage stability of winter maximum network before and after SCORPF.

4.5.6 Three stage SCORPF applied to 24 offline network studies

The results shown in Figure 4-14 verify that the three stage SCORPF approach consistently managed to reduce the active transmission losses in all of the manually optimised network studies produced by TR engineers. From these results the average reduction in active transmission losses with the three stage approach was 1.9%, this represents an improvement over the one stage approach's losses reduction result presented in section 4.4.2. The active losses reduction achieved using the three stage approach is equivalent to reducing the annual carbon dioxide emissions from generators by approximately 64,000 tonnes. This losses reduction value is more accurate than the previously reported value by Macfie et al. [19] since additional network studies were included in this study.

While most SCORPF studies in Figure 4-14 showed a reduction in generator reactive utilisation, there were several studies that showed generator reactive utilisation increasing. An increase in generator reactive utilisation would not be acceptable in practice, because the extra generator reactive utilisation cost would be greater than the transmission losses saving under the current incentive scheme arrangements. This issue can be resolved by applying extra constraints to prevent undesirable increases in generator reactive utilisation – this will be discussed in Chapter 6.

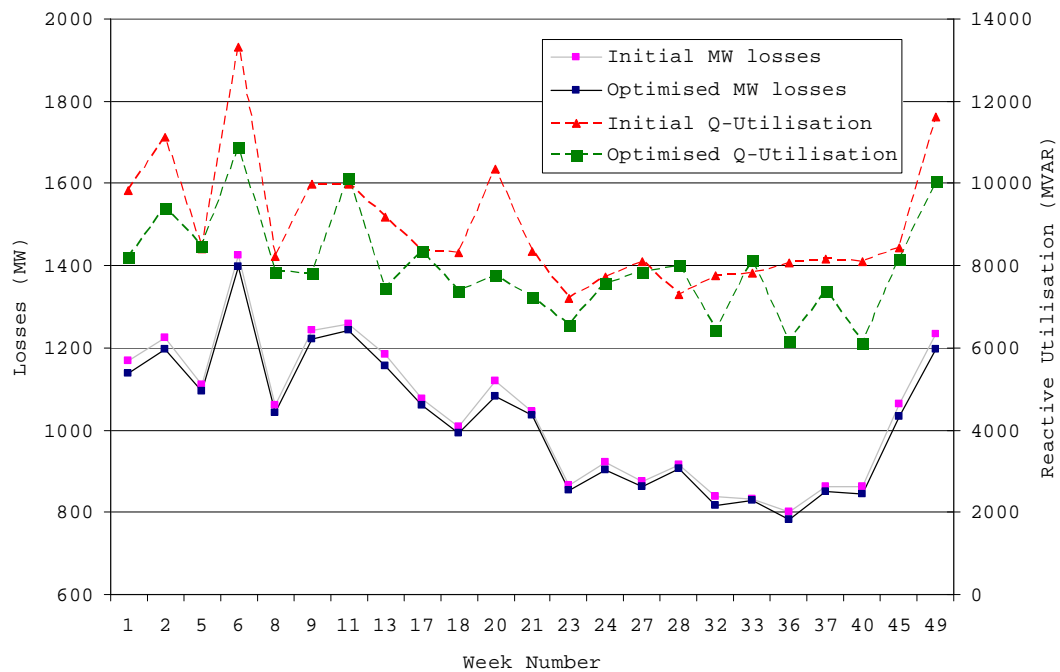


Figure 4-14. Initial offline network study results and corresponding SCORPF results obtained using the three staged technique.

4.6 Summary

This chapter described the modelling process used to formulate the offline GB transmission network SCORPF problem, which included an explanation of the controls and constraints included in the formulation. A method of validating and incrementally improving the modelling technique was also presented. One stage SCORPF results were then presented in order to demonstrate the potential for these techniques to reduce active losses. The SCORPF solutions were secure against all of the credible single and double circuit outages that are routinely considered by ENCC engineers. The sensitivity of the SCORPF active losses result to changes in the constraint limits and number of optimisable shunt control variables was also quantified.

This chapter introduced a multi-stage SCORPF technique that could be used as the basis of a tool to help reduce operational active transmission losses in offline network plans. An issue with the standard one stage approach was that it rounded discrete controls to their nearest physical value at the end of the optimisation process causing sub-optimality or infeasibility. A multi-stage approach was able to resolve the infeasibility by appropriately moving continuous controls while keeping discrete controls fixed. A novel three stage was also presented, this approach was evaluated on a range of networks and managed to improve the overall losses reduction.

SCORPF results were presented for a range of offline network studies that had been manually prepared by ENCC engineers to validate the multi-stage techniques. These optimisation results have demonstrated that SCORPF can achieve a significant active losses reduction in addition to a substantial reactive volume reduction on average. The average losses reduction using the three stage approach was 1.9%, which is equivalent to an annualised reduction in carbon dioxide emissions of 64,000 tonnes. The optimisation also appeared to increase the voltage stability margin of the network.

The results that have been presented in this chapter have demonstrated that on occasion it is possible for the reactive generator utilisation to increase when performing SCORPF with the transmission losses minimisation objective. Chapter 6 will present several alternative multi-objective approaches that can help resolve this issue.

These results have also revealed that the rounding of discrete variables may have been producing sub-optimality in the final solution that was not resolved with any of the multi-stage techniques. Chapter 5 proposes several alternative shunt rounding techniques that were able to find improved solutions compared to the standard technique when solving problems that included a large number of discrete optimisable shunt controls.

The main focus of Chapter 4 has been to demonstrate that secure losses reduction can be achieved using SC-ORPF techniques on practical large scale network models. A novel multi-stage technique was also presented. The main focus of Chapter 5 is significantly different as it will propose and evaluate several novel shunt rounding techniques.

Chapter 5

Mixed Integer SCORPF Technique for Loss Reduction

5.1 Introduction

As Great Britain's (GB) electricity transmission network operator, National Grid has a responsibility to securely operate the high voltage transmission network in England, Wales and Scotland. Macfie et al. demonstrated in 2009 [19] that operational active losses reduction was achievable in offline GB transmission network plans. These studies utilised the active transmission losses reduction objective and were based on the SCORPF technique that was described in chapter 4. The author noted that large numbers of discrete shunt devices were being treated as continuous control variables in the main optimisation [84], which were rounded to their nearest discrete step at the final iteration. This rounding was found to degrade optimality and potentially create infeasibilities. The GB transmission network includes around 270 shunt capacitors and shunt reactors, which provide an important source of reactive power that does not need to be procured from the market as the equipment is owned and operated by National Grid. It is therefore important that shunt capacitor and shunt reactor controls are included in the optimisation problem. This chapter proposes and presents results from several techniques that can easily be incorporated into an existing SCORPF program to solve the discrete switching problem more effectively than existing techniques will allow. The chapter begins with detailed descriptions of several novel shunt rounding techniques that are later demonstrated to produce SCORPF solutions that have lower active losses. The shunt rounding techniques are compared over a range of IEEE standard test network models and large-scale GB transmissions network models. Extensive results are presented including details of solutions times and the sensitivity to various parameters. Finally an enhancement to the shunt rounding technique will be described that can solve the full SCORPF

problem in a reasonable time on large-scale GB transmission network models, while ensuring that the solution is secure against 800 contingency cases.

5.2 Limitations of Existing MINLP Techniques

Liu, Papalexopoulos and Tinney describe two techniques for solving the mixed integer non-linear programming (MINLP) problem on large-scale power networks [99]. The first technique executes ORPF and then fixes all discrete controls to their nearest physical value. The second technique executes the first technique and then solves the optimisation problem again with only continuous control variables. The final solution from these techniques may not be optimal or secure because of the discretization process. For instance if the continuous optimisation solution required 52% of a 60 MVar capacitor, this capacitor will be switched in by both techniques. This may then create a voltage violation that cannot be resolved with the available continuous controls. The final solution would not be secure, which would limit its practical relevance.

Most commercially available ORPF programs are still based on the rounding techniques described above. Recent studies by Karoui et al. [24] and Ramos, Exposito and Quintana [77], which modelled areas of the European transmission network, used a rounding technique. Ramos, Exposito and Quintana utilised the rounding technique when the discrete step size of a shunt was small and a heuristic technique when the step size was bigger.

The operational shunt switching problem is analogous to the optimal capacitor placement problem. The optimal capacitor placement problem is widely regarded in the literature to be non-deterministic (NP) complete – this means that it is almost certain that finding the global minimum cannot be computed efficiently [28]. The computational complexity of combinational approaches increases exponentially with the number of discrete control variables and therefore becomes intractable for large-scale power systems. Therefore it has been suggested that it is more efficient to obtain a near optimal solution.

Combinational search optimisation techniques such as genetic [14], tabu-search [49], particle swarm [49] and simulated annealing [49] can be used to solve the MINLP ORPF problem. However there are several issues associated with using these techniques. Firstly these techniques are non-polynomial and do not therefore scale up well for large-scale power system problems. They are computationally rigorous techniques, which have a computation time that is exponential with the number of discrete variables. Secondly, the success of these algorithms often depends on the tuning of algorithmic parameters [100].

Modern mixed integer solvers often use branch-bound based techniques to solve the generalised mixed integer problem. Jabr [28] suggested a technique that uses a modified version of the branch-bound technique to solve this mixed integer problem. The modification consisted of a heuristic that essentially limits the search space that the branch-bound algorithm needs to explore, thus reducing the execution time of the solver. This technique was demonstrated to work in a reasonable time with 25 integer variables, but it was not able to scale up to solve large-scale power system problems.

To solve the mixed integer problem involving large numbers of shunt capacitors/reactors Liu, Papalexopoulos and Tinney [99] proposed utilising a quadratic penalty function associated with each discrete control. These penalty functions could be defined in such a way as to penalise continuous values so that the optimisation would favour the discrete solutions. Papalexopoulos proposed taking a tangent to the quadratic penalty function at the current operating point. This function needed to be regularly updated in order to preserve the quadratic nature of the penalty function. The main issues with this approach included determining the magnitude of the penalty function, timing its introduction, determining the criteria for updating, incorporating limit enforcement logic and determining an effective technique for fixing to a discrete step. The optimisation process was at risk of being trapped by the penalty function in a local minimum preventing it from finding a more optimal area of the solution space.

Liu et. al. [101] applied the penalty function shown in Figure 5-1 to minimise the non-convexity in the objective function. Liu extended a non-linear interior point

technique with his proposed penalty function approach and tested it on networks ranging in size from 14 busbars to 538 busbars. No comparison was made with an exhaustive combinational technique, so it is not known how successful this technique was at locating the global minimum. One of the drawbacks with this penalty based technique was timing the introduction of the penalty functions.

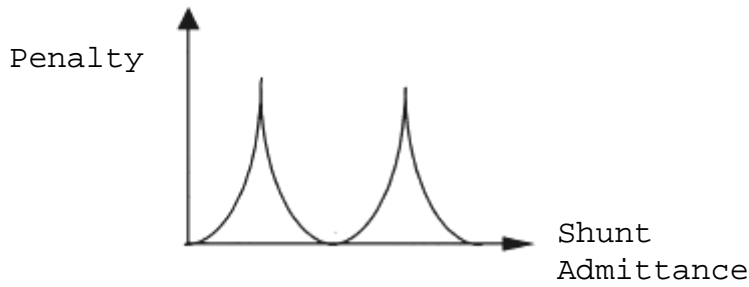


Figure 5-1. Quadratic penalty function proposed by Liu, Tso and Cheng [101]

Other techniques that are suggested in the literature for solving the MINLP ORPF problem include the technique developed by Chaves et al. [102]. A discrete task is executed after a solution to the continuous ORPF problem has been determined. The discrete task fixes all shunt controls that have a continuous value equivalent to being fully switched in, while leaving the other shunt controls as floating with a value of zero. Remaining floating shunt controls need to be rounded at the end of the optimisation process.

Recent literature [24, 25, 26, 27] reiterates that the discrete shunt switching problem essentially remains unsolved in a reasonable time on a complex large-scale power system. The next section of this chapter describes several novel shunt rounding techniques that can be readily implemented as an extension to an existing SCORPF program.

5.3 Proposed Shunt Rounding Technique

5.3.1 High-level procedure

Figure 5-2 illustrates how the proposed techniques can be integrated with an existing SCORPF solver. Firstly the network data is read and the main SCORPF is performed assuming all controls are continuous. At each iteration the optimal continuous solution from SCORPF is used to fix a subset of the floating shunt

controls to their nearest discrete value, based on either of the techniques explained in section 5.3.2 or 5.3.4. This process is then repeated iteratively until a stop condition is satisfied when either the maximum number of iterations has been reached or when all discrete controls are fixed. Any remaining floating discrete controls are then fixed to their nearest discrete value. Finally a round of optimisation is performed using only continuous controls to remove any violations caused by the final discretization.

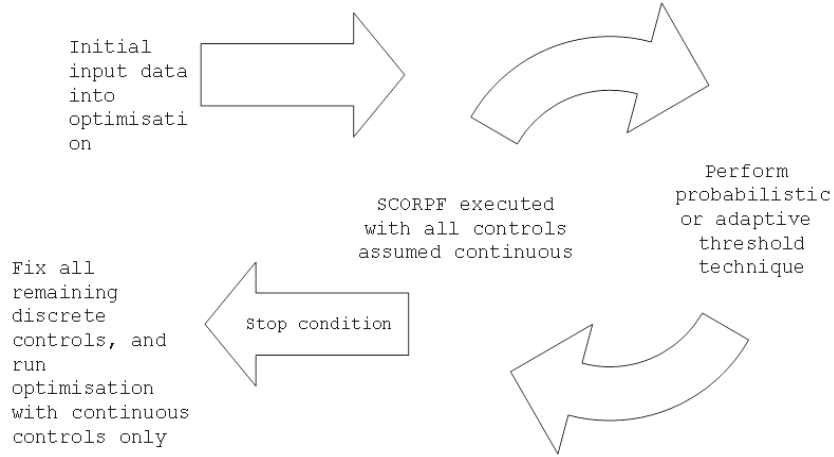


Figure 5-2. Procedural chart showing the enhanced SCORPF process.

The main SCORPF component of this process was solved using the same reactive controls and constraints that were described in section 4.3. A single objective function was minimised by the optimisation process, which was the total active transmission losses:

$$Losses_{Tot}^{AC} = \sum_{L=1}^{n_L} G_{ik} (V_i^2 + V_k^2 - 2V_i V_k \cos \theta_{ik}) \quad (5-1)$$

L is a line with conductance G connecting the i th node to the k th node, and n_L is the total number of lines on the network. V and θ refer to the nodal voltage magnitude and angle.

5.3.2 Probabilistic technique

The probabilistic technique examines the continuous solution of each optimisable shunt control at every iteration of Figure 5-2, fixing a subset of the shunts to the nearest discrete value. The probability of fixing is determined by how far the continuous solution is from the nearest discrete value on a normal distribution, as illustrated in Figure 5-3. Essentially if the continuous value of the shunt is close to

a discrete value there is a high chance of fixing and if a shunt is in the middle of the range of discrete values there is a low chance of fixing.

The probability distribution shown in Figure 5-3 can be used to calculate the probability that a shunt is fixed in and is based on the normal distribution which is given by:

$$\text{Scaled normal distribution} = \frac{s}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad (5-2)$$

$$\approx e^{-20(x-1)^2}$$

μ and σ are the mean and standard deviation of the distribution, x is the continuous value of the shunt as a percentage of its switched in value. s is a scaling value.

An investigation was carried out to empirically determine appropriate values for the scaled normal distribution. The parameters $s=0.38$, $\mu=1$ and $\sigma=0.15$ were found to give the required curve shape illustrated in Figure 5-3. This curve shape is considered most appropriate because it has a probability of one at the sides, and zero in the middle region.

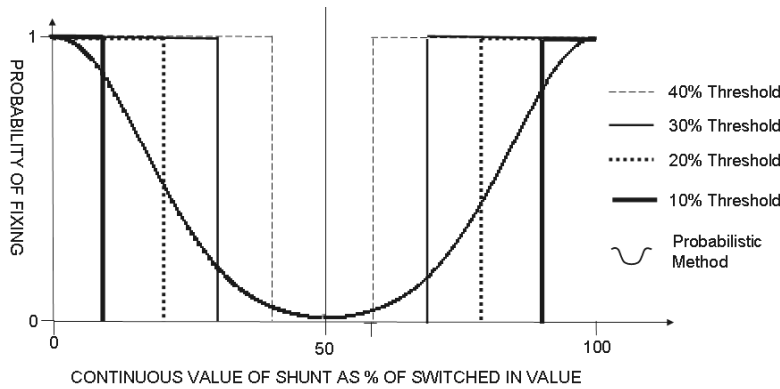


Figure 5-3. Probability of shunt fixing in the probabilistic and adaptive threshold techniques.

5.3.3 Probabilistic pseudo code

The following pseudo code describes the probabilistic technique:

FOR $i=1$ to the total number of controllable shunts

IF $\text{absolute}(S_{ci}/S_{mi}) > 0.5$

```

        AND  $S_{pi}=1$ 
        AND  $FIXSHUNT(S_{ci}/S_{mi})=TRUE$ 
    THEN  $S_{ci}=S_{mi}$  ;  $S_{pi}=0$  ;  $CNT=CNT+1$ 
        ELSEIF  $absolute(S_{ci}/S_{mi}) < 0.5$ 
        AND  $S_{pi}=1$ 
        AND  $FIXSHUNT(S_{ci}/S_{mi})=TRUE$ 
    THEN  $S_{ci}=0$  ;  $S_{pi}=0$  ;  $CNT=CNT+1$ 
    ENDIF
ENDFOR

```

```

FUNCTION  $FIXSHUNTS(S_{ci}/S_{mi})$ 
R=Random number between 0 and 1
IF  $absolute(S_{ci}/S_{mi}) > 0.5$ 
    AND  $R < \exp(-20(S_{ci}/S_{mi}-1)^2)*PF$ 
    THEN Return TRUE
ELSEIF  $absolute(S_{ci}/S_{mi}) < 0.5$ 
    AND  $R < \exp(-20(S_{ci}/S_{mi})^2)*PF$ 
    THEN Return TRUE
ELSE Return FALSE

```

S_{ci} is the i 'th shunt solution value, S_{mi} is the i 'th shunt switched in value, S_{pi} is a flag determining the optimisation availability status of the i 'th shunt. PF is the probability factor. CNT is a counter that returns the number of shunts that were fixed.

The probabilistic technique has three adjustable parameters – probability factor, maximum number of iterations and a stop condition value. The probability factor scales the probability of fixing, so a low value means that the technique will take longer to fix all the shunts. The probabilistic technique will halt when the stop condition has been satisfied or the maximum number of iterations has been reached. The stop condition is satisfied when the number of shunts fixed during two consecutive iterations of Figure 5-2 is less than the stop condition value.

5.3.4 Adaptive threshold technique

The adaptive threshold technique also examines the continuous solution of each optimisable discrete control at every iteration as shown in Figure 5-2, fixing a subset of the shunts to their nearest discrete value. A shunt is fixed if the continuous solution is within a threshold distance of a discrete value. The first iteration of the adaptive threshold technique fixes only those shunts that are within a 10% threshold from their discrete value, the second iteration applies a threshold of 20%, the third iteration applies a threshold of 30% and then the ten remaining iterations apply a threshold of 40%. The maximum number of iterations parameter is user definable.

5.3.5 Adaptive threshold pseudo code

The following pseudo code describes the adaptive threshold technique:

FOR i=1 to the total number of controllable shunts

IF absolute(S_{ci}/S_{mi}) > 0.5

AND $S_{pi}=1$

AND (S_{ci}/S_{mi}) > (1-threshold)

THEN $S_{ci}=S_{mi}$; $S_{pi}=0$; CNT=cnt+1

ELSEIF absolute(S_{ci}/S_{mi}) < 0.5

AND $S_{pi}=1$

AND (S_{ci}/S_{mi}) < threshold

THEN $S_{ci}=0$; $S_{pi}=0$; CNT=cnt+1

ENDIF

ENDFOR

5.3.6 Mid-step logic

If a large portion of controllable shunts have a continuous optimisation solution that is between discrete steps, then a number of iterations could pass without fixing any of the shunts either in or out. This could mean that the final solution from the proposed technique may not be better than directly rounding the continuous optimisation solution result. The mid-step logic provides a solution to this issue.

The mid-step logic that is shown in Figure 5-4 works by extending the Figure 5-2 process. The extra steps shown in Figure 5-4 help to solve the problem described in the previous paragraph, because when one shunt is fixed to a discrete value then it is often the case that the continuous optimisation solution of the other shunts will move closer to a step value. The mid-step logic will activate when all of the continuous optimisation shunt solutions are in the middle region between discrete steps. A decision is then made as to which single shunt to fix using an appropriate technique, before moving to the next iteration. The fixing techniques that have been investigated within this research project have included:

- Fixing the largest floating shunt.
- Fixing the smallest floating shunt.
- Randomly fixing a shunt.

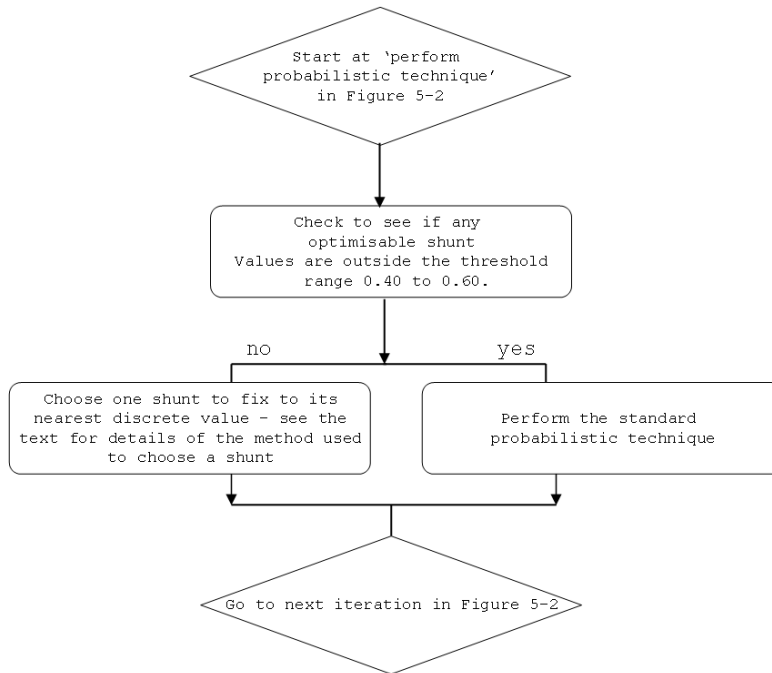


Figure 5-4. Mid-point logic extending process shown in Figure 5-2.

5.4 Measuring the Performance of the Proposed Techniques

5.4.1 Network models

Widely recognised standard network test models ranging in size from 6 to 118 buses were modified to evaluate the performance of the proposed shunt rounding techniques. The 6 bus network was the Ward Hale test model [96], while the other networks were all standard IEEE test models [103]. The standard IEEE test

models included a 14-bus, 30-bus, 57-bus and 118-bus case. Additional switchable capacitors and reactors were modelled at PQ buses with susceptance sizes determined by twice the reactive support requirement at the corresponding bus, thus making the optimisation more challenging. The 57-bus and 118-bus network test cases were modelled with 6 and 16 contingency cases respectively - each contingency case contained the outage of a single transmission line. The transmission lines were chosen in the order of those with the largest pre-fault flow. A custom two bus binary test network was also investigated with the parameters given in Table 5-1. Table 5-2 lists the shunt capacitors and reactors that were added to each small-scale network test model and Table 5-3 lists parameters describing all of the small-scale networks and four GB large-scale test models. The full specification for every network is available from [96] and [103]. Figure 5-5 presents a diagram showing a schematic representation of the Ward Hale six bus network test model.

	Type	Generation	Load
Bus 1	Slack	Slack	0
Bus 2	PQ	0	1.8 + j0.9

	From	To	R	X	B/2
Branch1	1	2	0.009615	0.04808	0.01

Table 5-1. Binary two bus test network specification

Large-scale GB transmission network models were also used to evaluate the performance of the proposed shunt rounding techniques. Each GB transmission network model was a manually secured day-ahead system representation with topology, demand, generation and controls all representative of what was likely to occur on the real system. The shunts were initialised to a flat start in order to provide a fair starting point for comparing the optimisation solutions from the proposed techniques. Typically each GB network model consisted of around 3500 nodes, 3000 lines, 2500 transformers, 80 continuous generator voltage target controls and 270 discrete shunt controls. Initial research focussed on just four GB transmission network models, as shown in Table 5-3, with only one of these networks including contingency case data.

Name of System	List of shunt MVAR sizes added to the network models (Bus number to which additional shunt is connected)
Binary Test 2 Bus	100(2), 50(2), 25(2), 12.5(2), 6.25(2), 3.13(2), 1.56(2)
Ward and Hale 6 Bus	0.4(5), 0.2(5), 0.1(5), 0.05(5), 0.025(5), 0.0125(5), 0.00625(5), 0.5(6), 0.25(6), 0.125(6), 0.0625(6), 0.03125(6), 0.015625(6), 0.007813(6)
IEEE 14	-40(4), 14.4(10), 4.85(11), 4(12), 13.2(13), 10.7(14)
IEEE 30	15(3), 13(7), 36(12), 3.5(14), 5.5(15), 5(16), 6.4(17), 1.8(18) 6.4(19), 16(21), 4(24), 0.45(25), 4.5(26), 15(27), 2.2(29), 5(30) 8(22), 3.5(23)
IEEE 57	-95(4), -120(10), -72(11), -50(13), -110(14), 25(16), 34(17) 130(18), 35(20), -35(21), 20(38), 80(41), 8(42), 10(44), 90(45) 120(46), 24(47), 62(49), 22(50), 129(51), 18(52), 12(53) 50(55), 17(56), 18(57)
IEEE 118	-87(5), 45(15), 74(3), 30(9), 58(11), 35(13), -225(17), 22(20), 17(21), 15(22), 20(23), 17(28), 300(30), 20(33), 28(35), 187(38), 21(39), 21(41), -13(44), 19(45), -13(48), 24(51), 11(52), 21(53), 45(60), 400(63), 300(64), 26(67), 300(68), 42(71), 86(75), 115(78), 26(79), 160(81), 15(83), 36(84), 34(86), 69(88), 32(93), 38(94), 64(95), 15(97), 10(98), 29(101), 36(102), 53(106), 33(114), 14(115), 15(117), 105(118)

Table 5-2. Modifications to the standard network test models

Name of System	Number of Buses / Branches	Number of Generators	Number of Discrete Controls / Continuous Controls	Number of modelled Contingencies
Binary Test 2 Bus	2/1	1	7 / 0	0
Ward-Hale 6	6/8	2	14 / 0	0
IEEE 14	14/20	5	6 / 0	0
IEEE 30	30/41	6	18 / 0	0
IEEE 57	57/80	7	25 / 0	6
IEEE 118	118/186	54	50 / 0	16
GB 1	3465/5213	223	263 / 73	0
GB 2	3587/5397	303	300 / 94	0
GB 3	3450/5186	234	262 / 80	0
GB 4	3551/5393	253	269/81	40

Table 5-3. Parameters describing the standard network test models and the four GB network models that were initially investigated.

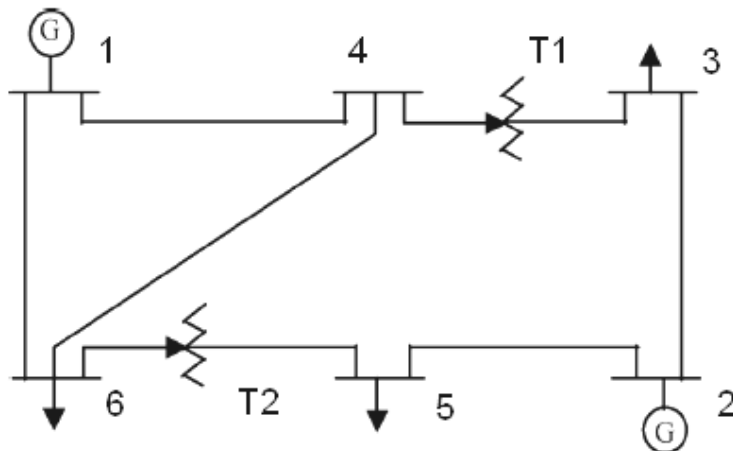


Figure 5-5. Ward Hale six bus network test model.

5.4.2 Measuring the baseline

The network models described in Table 5-2 and Table 5-3 were used to evaluate the performance of the proposed techniques. The solutions from the standard test networks obtained from the proposed techniques were compared against the power flow solution from the initial network, the standard shunt rounding ORPF and a non-feasible ORPF in which all controls were assumed to be continuously varying. The solutions from the proposed techniques were also compared against the solutions from the mixed integer non-linear programming algorithm MINLP developed by Fletcher and Leyffer [104]. This mathematical programming method implements a branch-and-bound technique that searches a tree with nodes corresponding to continuous non-linearly constrained optimisation problems. The MINLP algorithmic method utilises branch and bound, interlacing the continuous and integer optimisation problems so that the non-linear part of the problem is solved while searching the branching tree. In order to achieve this the MINLP algorithmic method implements early branching and does not therefore solve the non-linear problem to optimality at each branch point, which has the possible drawback that the global optimal solution may not be found.

The NEOS optimisation web service was used to execute MINLP [105]. To do this it was first necessary to formulate an AMPL version of each network optimisation case, AMPL is an algebraic language that allows high-complexity optimisation problems to be defined.

All the standard network test cases up to 118 buses were converted into AMPL code. Network constraints and controls were implemented to identically represent the constraints and controls solved by the SCORPF.

The large-scale GB power network test cases could not be encoded in AMPL, so a MINLP result could not be derived. The proposed techniques were therefore compared against a two staged SCORPF standard rounding method. This standard approach begins with a stage of SCORPF assuming all controls are continuously varying and then sets all discrete controls to their nearest value; this is followed

by a second stage of SCORPF utilising only continuous control variables to remove any violations. These results are labelled ‘Rounding’ in Table 5-5.

5.4.3 Executing the investigation

The proposed techniques were written and executed in MATLAB version 7.0 on a P4 3GHz with 512MB memory. On a full scale constrained GB transmission network model the probabilistic technique typically took nine minutes to find a solution.

To meaningfully compare the output from the various proposed techniques we needed to execute the probabilistic technique one hundred times with different random number generator seed states. The mean and standard deviation of the active transmission losses solutions were then determined. A maximum of 20 iterations was allowed for all of the techniques. The output was then compared to the results from the baseline approaches that were described in section 5.4.2.

5.5 Results and Analysis

5.5.1 Parameter sensitivity analysis

The proposed probabilistic shunt rounding technique had several heuristic parameters that needed to be assigned a value. This value assignment choice was initially arbitrary, so a more rigorous approach was required. Determining appropriate parameters involved executing the heuristic around 1000 times on each test network – each time varying the stop condition and probability factor values slightly and then taking the average of five result runs. The results of these investigations are presented in the form of 3D surfaces showing either the averaged absolute losses value or the averaged number of iterations, against the probability factor and stop condition values. Figure 5-6 shows the results surface from a summer time GB transmission network optimisation and Figure 5-7 shows results from a winter time optimisation. These results surfaces have been rotated in order to give the clearest view of the data, which means that care needs to be taken when reading the axis.

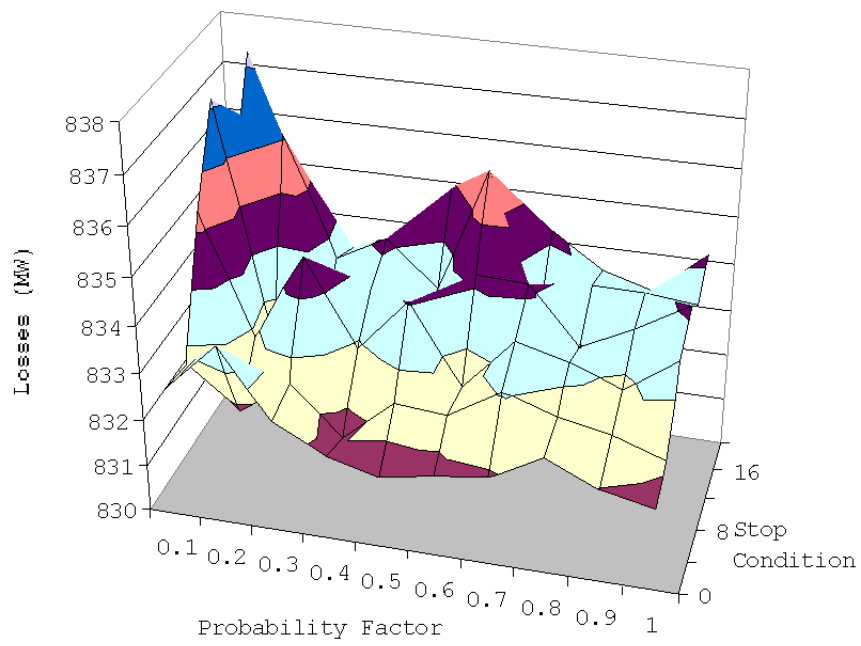


Figure 5-6. Active losses sensitivity on a winter GB network model.

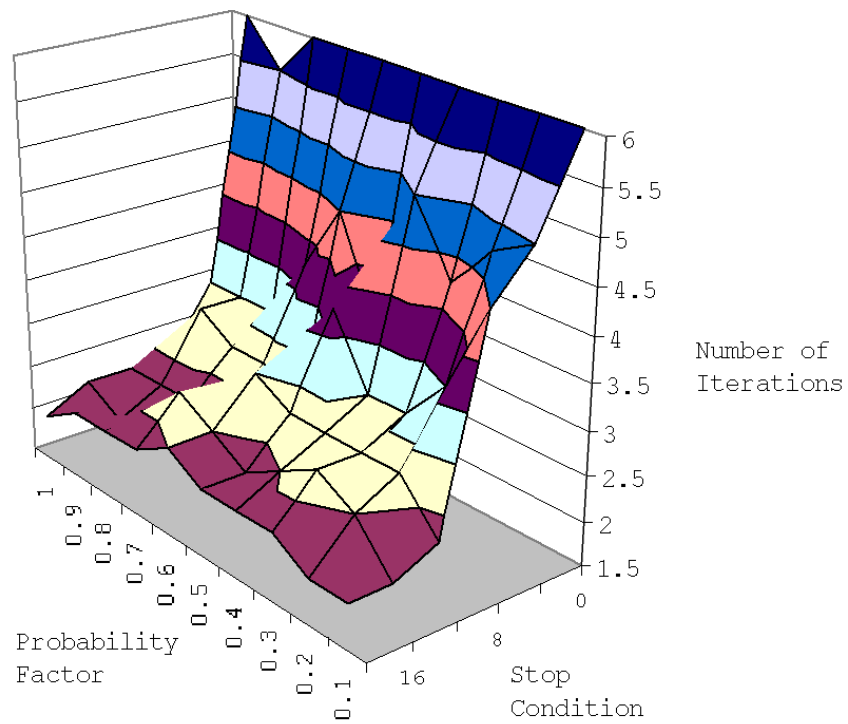


Figure 5-7. Number of iterations sensitivity on a winter GB network model.

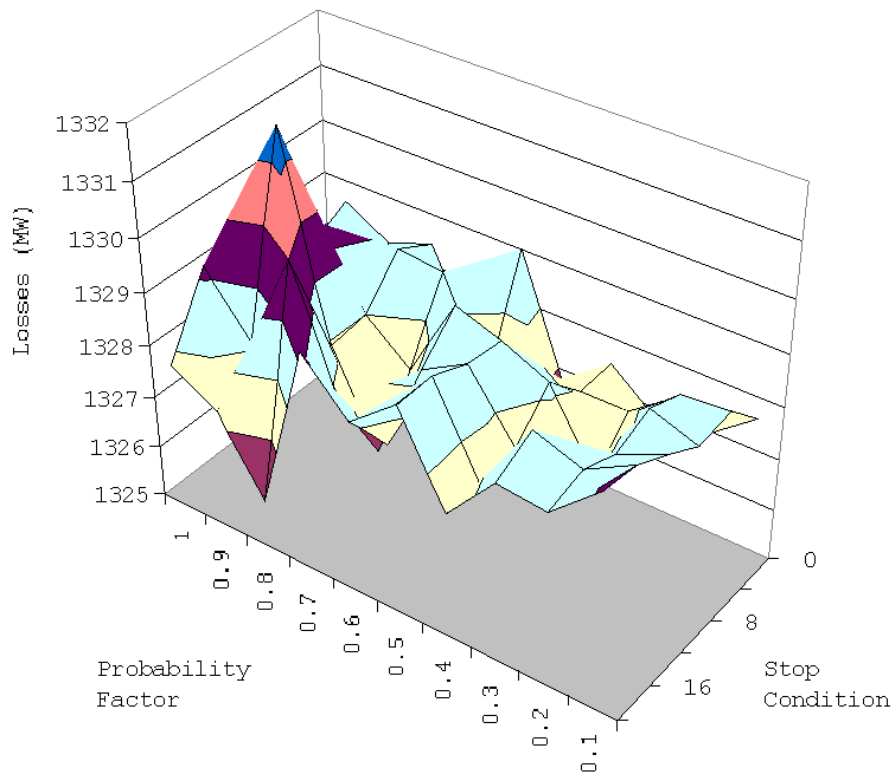


Figure 5-8. Active losses sensitivity on a summer GB network model.

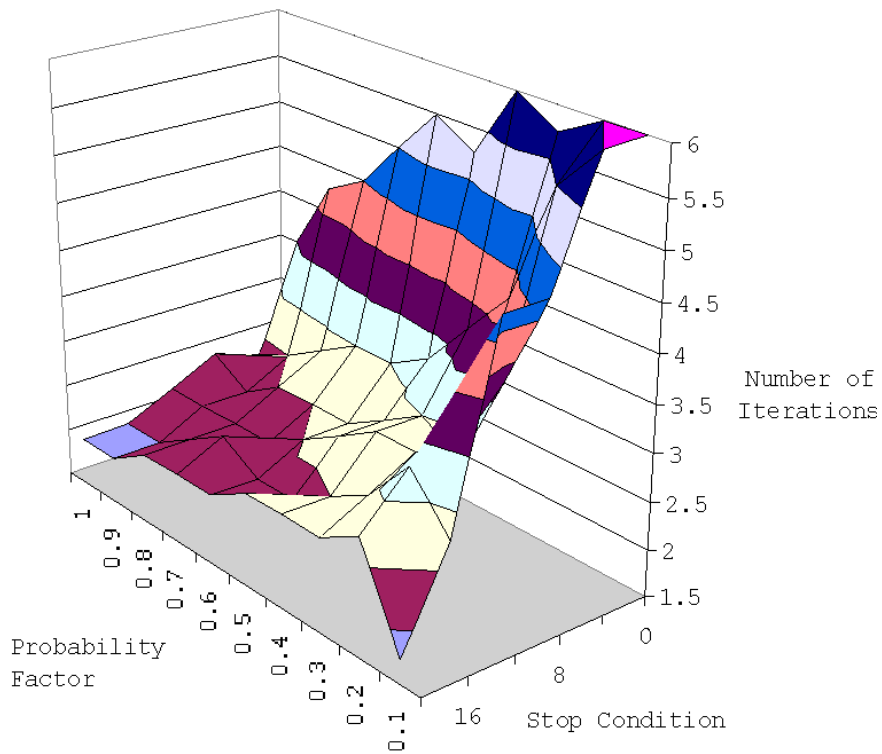


Figure 5-9. Number of iterations sensitivity on a summer GB network model.

The surfaces presented in Figure 5-6 through to Figure 5-9 have allowed appropriate probabilistic technique parameter values to be chosen, which will be useful in the next stage of the investigation. From these figures the best value for

the probability factor was determined to be 0.4, this low value means that more iterations need to be performed before finding a solution, but the solution will have a lower cost. From these results it is also possible to determine that the best value for the stop condition is zero, this value implies that the process should continue until the process does not fix any shunts during two consecutive iterations. A maximum number of iterations of 20 was found to be reasonable. These parameters were chosen by visually inspecting the figures 5-6 to 5-9 and determining reasonable values to obtain the desired behaviour. The author acknowledges that a range of values could give similar results.

5.5.2 Binary two bus network results

The specification describing the two bus test network was presented in Table 5-1 and Table 5-2. Seven shunts were attached to the demand side bus with the size of each shunt being set at a value twice that of its neighbour. Considering the design of this network an ideal integer optimizer should be able to achieve a discrete shunt switching solution that is very close to the continuous optimisation result. The optimisation results from this network are presented in Table 5-4. Results obtained from the standard rounding and adaptive threshold techniques have not been included, since these techniques failed to produce a reduction in the value of the active losses. The probabilistic technique results achieved a substantial reduction in the value of the active losses. The total shunt susceptance value shown in the table has been obtained by summing the value of the switched in shunts from the corresponding solution, and is given by the following equation:

$$Total_B = \sum_i s_i B_i \quad s = \frac{1 - switched_in}{0 - switched_out} \quad (5-3)$$

s_i is the switching state and B_i is the susceptance of the i^{th} shunt.

As indicated in section 5.3.6 the probabilistic technique can fail to fix shunts when many of them are between discrete steps, to solve this problem a mid-step logic was presented. Table 5-4 includes results from this mid-step logic, with the various techniques, which were described in section 5.3.6, used to fix the shunts. Note that all of the probabilistic results in the table are averaged results taken from 100 trials.

	Original Losses (pu)	Optimised Losses (pu)	Optimised shunt pattern	Total shunt susceptance (pu)
Baseline				
MINLP	0.044664	0.03228	1000101	1.078125
Continuous	0.044664	0.03228	NA	
Probabilistic				
no mid-step logic	0.044664	0.03424206	NA	1.071805
mid-step smallest	0.044664	0.033723	NA	0.744152
mid-step largest	0.044664	0.03233835	NA	1.06039
mid-step random	0.044664	0.03294585	NA	1.017031

Table 5-4. Compares SCORPF active loss minimisation solutions using the binary two bus test network.

The probabilistic technique produced a solution that had significantly lower active losses than the original network. The probabilistic technique with mid-step logic that switches in the largest shunt first produced an even better solution than the probabilistic technique on its own. For comparison the solution from MINLP produced had the lowest active power losses, however the MINLP optimisation process does not scale up well to solve large-scale network problems. The non-physical continuous optimisation results have been included in the table for completeness.

5.5.3 Ward-Hale network results

Figure 5-10 shows the losses objective function contour surface of the Ward Hale 6 bus network. The objective function was mapped over a range of susceptance values for shunts attached to bus 5 and bus 6. The solutions from the standard shunt rounding method and the adaptive threshold technique were identical as all shunts were switched out. The figure indicates that MINLP has correctly located the minima at (0.24, 0.18). The probability factor of the probabilistic technique was varied with the values 0.1, 0.5 and 0.9 - the solutions are marked on the figure as P0.1, P0.5 and P0.9 respectively. The P0.9 and P0.5 probabilistic solutions lie on the flat area close to the optimal MINLP solution.

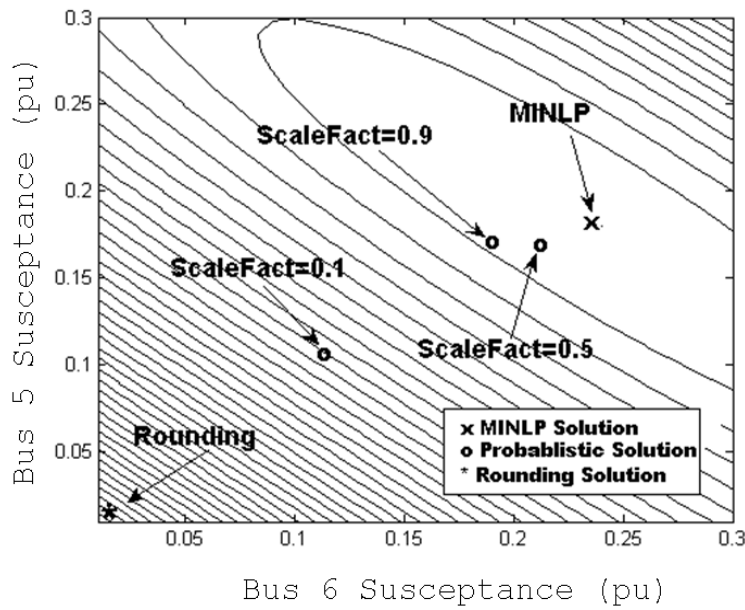


Figure 5-10. Compares standard shunt rounding, probabilistic and MINLP solutions on the Ward-Hale test network.

5.5.4 Comparison of optimisation results

Table 5-5 and Table 5-6 show the optimisation results from the standard test cases and four example large-scale GB transmission network cases. The first five rows show ORPF standard test case results that are not security constrained, the next two rows show SCORPF results from the IEEE 57 and IEEE 118 bus network cases with contingencies constraining the optimisation. The following three rows show ORPF results from large-scale GB network cases. The final row shows SCORPF results from a GB network case with forty contingency cases constraining the optimisation. The large-scale GB network cases considered the full mixed integer optimisation problem, which meant that continuous generator voltage target, continuous SVC voltage set-point, discrete shunt capacitor and discrete reactor controls were included in the optimisation.

Table 5-5 compares the active power loss results, obtained from the network cases that were described in the previous paragraph, using a variety of mixed-integer optimisation approaches. The columns of the table relate to the results from the initial power flow, non-physical SCORPF assuming all controls are continuously varying, the standard rounding method, MINLP, the adaptive threshold technique and the probabilistic technique. No mid-step logic was applied, as there was no

time during the execution of the technique when all shunts had continuous values that were exactly between discrete steps. The columns in Table 5-6 present the percentage improvement scores of the proposed techniques and MINLP relative to the continuous case. A score of 100% indicates that the discretization algorithm has performed as well as the non-physical continuous solution and 0% indicates the solution is no better than the rounding method. These percentage values are determined using the following relationship.

$$\frac{\text{Rounded_Solution} - \text{Solution}}{\text{Rounded_Solution} - \text{Continuous_solution}} \quad (5-4)$$

Solution is the magnitude of power losses from the adaptive threshold, probabilistic or MINLP technique. *Rounded_solution* is the magnitude of power losses in the standard rounding method's solution and *Continuous_solution* is the magnitude of power losses in the non-physical SCORPF continuous solution.

For example consider the WardHale 6 bus probabilistic reduction that relative to the continuous case.

$$\left(\frac{10.213 - 8.912}{10.213 - 8.674} \right) = 1.301 / 1.539 = 0.845$$

As a percentage this is 84.5%, which is the value shown in the third column of Table 5-6. This value indicates that the probabilistic technique has done well compared to the non-physical continuous solution.

P l o s s (M W)						
	Initial	Continuous	Rounding	MINLP	Adaptive	Averaged Probabilistic
WardHale 6	10.210	8.674	10.213	8.747	10.213	8.912 +/- 0.16
IEEE 14	13.358	13.240	13.358	13.334	13.358	13.334 +/- 0.14
IEEE 30	17.542	17.213	17.542	17.303	17.542	17.316 +/- 0.03
IEEE 57	28.620	25.720	28.620	27.924	28.620	27.386 +/- 0.26
IEEE 118	132.483	128.380	132.480	##	132.140	131.296 +/- 0.41
IEEE 57 + 6C	28.620	25.760	27.860	#	27.860	27.281 +/- 0.29
IEEE 118 + 16C	132.483	128.390	132.610	#	132.110	131.160 +/- 0.45
GB1	881.90	830.21	839.69	#	834.93	830.00 +/- 0.47
GB2	1414.20	1322.07	1368.39	#	1322.86	1323.38 +/- 0.52
GB3	916.69	890.83	902.54	#	894.69	892.57 +/- 0.47
GB4 + 40C	1239.68	1136.31	1139.46	#	1139.50	1136.83 +/- 2.54

Table 5-5. Comparison of the optimisation results for the test networks.

Reduction % in objective relative to continuous case*			
	Adaptive	Probabilistic	MINLP
WardHale 6	0.0	84.5	95.3
IEEE 14	0.0	20.3	20.3
IEEE 30	0.0	68.7	72.6
IEEE 57	0.0	41.6	26.9
IEEE 118	8.3	28.9	##
IEEE 57 + 6C	0.0	27.6	#
IEEE 118 + 16C	11.8	34.4	#
GB1	50.2	102.2	#
GB2	98.3	97.2	#
GB3	67.0	85.2	#
GB4 + 40C	-1.3	83.5	#

Table 5-6. Percentage improvement obtained by the techniques relative to the continuous case. *=see text for details of how these values were calculated.

In the standard network test cases the rounding method did not manage to achieve a reduction in power losses because the continuous optimisation solution of all the shunt devices was just below 50% of their capacity and therefore rounding had the effect of switching out all of these devices. In general the adaptive threshold technique did not manage to reduce power losses in the standard network test cases because the continuous optimisation solution value of the shunt devices was always outside of a threshold band. However, the probabilistic technique managed to reduce the power losses by an average of 3.6%.

Table 5-6 shows that large-scale GB network optimisation using the adaptive threshold technique achieved an average improvement score of 54%, while the probabilistic technique achieved an average improvement score of 92%. The improvement in the losses objective function was 1.15% and 1.40% for the adaptive threshold and probabilistic techniques respectively. On the GB4 network with 40 contingencies the adaptive threshold technique was found to cause a slight increase in the losses, which could be due to a combination of the ineffectiveness of the adaptive threshold technique to find a good solution on this problem and the non-convex nature of the optimisation problem.

Since the probabilistic technique is based on a random number generator it is essential to run multiple executions to assess its performance. The investigation process that was used was explained in section 5.4.3. Table 5-7 presents a statistical analysis derived from the multiple run results – notice that the standard deviation is small and the worst case values are still better than the standard rounding method.

P_{loss} (MW)	6 bus	IEEE 57 bus	IEEE 118 bus
Average	8.912	27.386	131.296
Standard Deviation	0.163	0.261	0.410
Best	8.747	27.109	130.790
Worst	9.862	28.409	132.270

Table 5-7. Statistics of variation in the probabilistic technique's solution.

5.5.5 Analysis of the probabilistic technique results

Figure 5-11 shows how the value of active losses evolves with the number of iterations on the 6 bus and 118 bus networks during the execution of the probabilistic technique. The figure shows that the behaviour of the active losses is similar for both of these networks. At each iteration of the probabilistic technique a number of shunts are fixed to the nearest discrete value, which typically causes a slight increase in active losses. Analysis of the shunt switching pattern revealed that the large rise in active losses near the end of the iterative process was due to shunts in the middle of their range being fixed. Figure 5-12 illustrates the effect on the averaged probabilistic solution, for the 6 bus and 118 bus networks, when the probability factor was varied. The error bars indicate the standard deviation in the solution value. It can be seen that the 6 bus network results varied smoothly with a minimum average active losses and low standard deviation at a probability factor of 0.9. The results on the 118 bus network were less smooth, but still indicated that a probability factor of 0.9 was reasonable. For comparison the results from the standard shunt rounding method are also included in Figure 5-12 indicated by the horizontal lines.

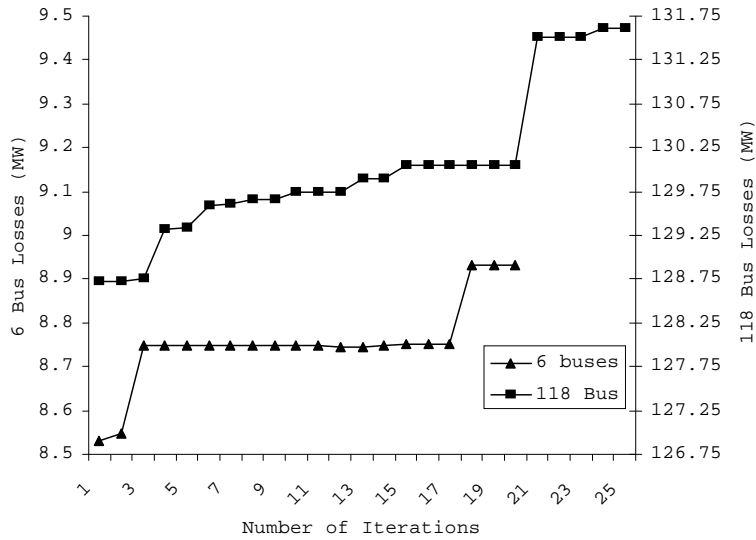


Figure 5-11. Variation of active power losses with the number of iterations of the probabilistic technique.

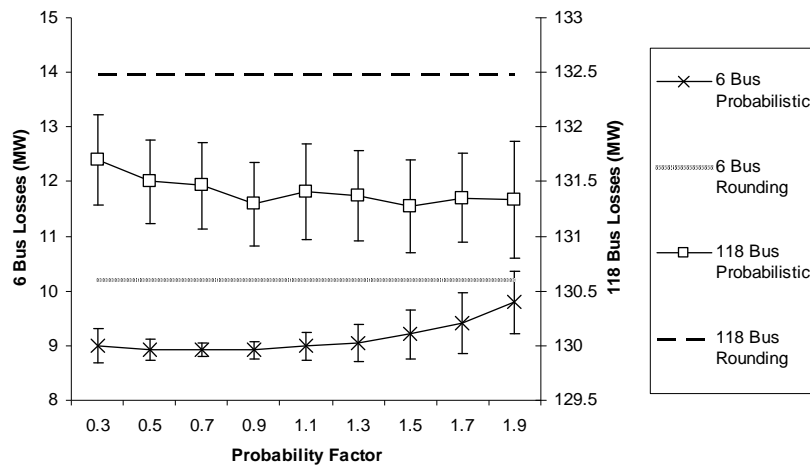


Figure 5-12. Variation in the average active losses from the probabilistic technique with different probability factors.

5.5.6 Solution time comparison with MINLP

As indicated in Table 5-5 MINLP was used to solve the standard network test case discrete optimisation problems. MINLP does not scale well and cannot efficiently calculate the solution to large-scale problems or problems involving a large number of contingencies. When a MINLP result could be evaluated, the probabilistic technique achieved at least 98% of the active losses reduction achieved by MINLP. The probabilistic technique found a solution that was better than MINLP on the 57 bus network case. The probabilistic technique was applied to more difficult problems involving large networks and networks involving a

number of contingencies. The probabilistic technique results were consistently better than the standard shunt rounding method results.

The solution time for MINLP to find a solution was recorded and compared to the probabilistic technique's solution time on the same network. The MINLP algorithm, which is based on branch and bound, is time exponential in the number of variables. This relationship is confirmed in Figure 5-13. The performance of the probabilistic technique was worse than MINLP on the Ward Hale 6 and IEEE 14 bus network test cases; however the performance on the IEEE 30 and 57 bus network test cases was significantly better than MINLP. The ratio of the time taken to solve the IEEE 57 bus network problem to the time taken to solve the Ward Hale network problem was 2.2 and 6,200 for the probabilistic technique and MINLP respectively.

Table 5-8 presents a comparison showing the scalability of the proposed probabilistic technique to the scalability of the penalty function based technique described by Liu, Tso and Cheng [101]. They performed their optimisation using a customised selection of standard test networks with discrete controls. The customisations were different to the customisations considered in this research, because Liu, Tso and Cheng were investigating discrete transformer taps while this thesis has concentrated on solving the large-scale discrete shunt despatch problem. Although it is not possible to directly compare results it is possible to compare the scalability of the algorithms as the number of discrete variables is increased. The ratio of time / number of discrete variables indicates the scalability. In the case of the probabilistic technique this ratio reduces as the problem size gets bigger indicating good scalability, but in the case of the penalty based technique this ratio gets larger indicating poorer scalability.

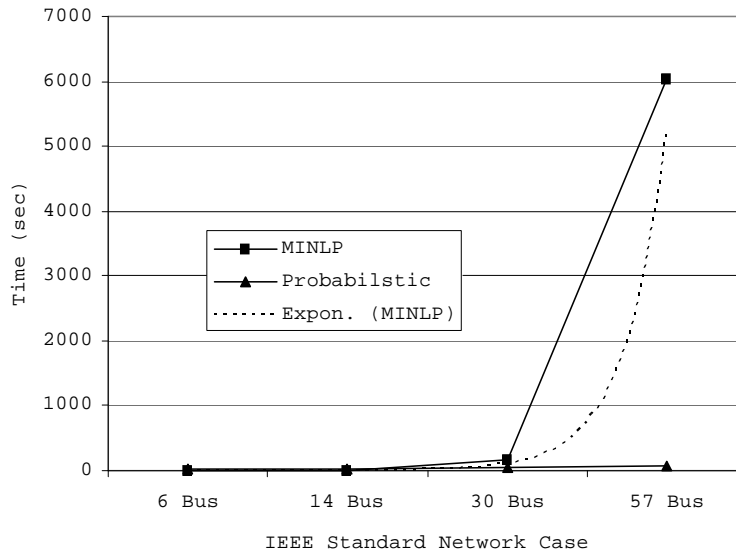


Figure 5-13. Solution time to solve the standard network integer optimisation problems using MINLP and the probabilistic technique.

Proposed probabilistic technique

Discrete variables	6	14	21	50	262
Ratio time/variables	5	1.9	2.9	1.4	1.4

Penalty based technique

Discrete variables	6	13	14	18	162
Ratio time/variables	0.3	0.5	0.3	1.4	6.0

Table 5-8. Scaling comparison with penalty function based technique used by Liu, Tso and Cheng. Comparison made with published results [101].

5.5.7 Solution time variation with the number of integer control variables

The sensitivity of the solution time to the number of discrete control variables included in the optimisation is of interest because it can be a limiting factor preventing an optimisation technique from being scaled up to solve practical large-scale power system problems. This section compares the proposed probabilistic technique, MINLP [104] and KNITRO [106]. KNITRO is a commercial mixed integer programming solver. Both MINLP and KNITRO solve the large-scale mathematical mixed integer optimisation problem using a branch and bound technique. It is useful to include both MINLP and KNITRO solvers in this comparative analysis, as they are both popular widely used optimisation solvers.

An IEEE 57 bus network optimisation problem was prepared in AMPL format, with the extra shunt devices listed in Table 5-2, using the process described in more detail by Macfie et al. [21]. The proposed probabilistic technique, MINLP and KNITRO solvers were then used to solve the optimisation problem. To investigate the scaling of the three algorithms the time taken to reach a converged solution was measured as the number of discrete controls was gradually decreased. The value of the active losses in the final solutions was also recorded. Figure 5-14 (a) shows the variation in the solution time against the number of discrete control variables, a cubic polynomial line of best fit has been added to each of the three sets of results with its equation. These results clearly illustrate how the MINLP and KNITRO solvers scale poorly with the number of discrete control variables compared to the scaling of the probabilistic technique. The equations describing the best fit lines confirm this observation, as the cubic term multiplier is bigger for the MINLP and KNITRO results than the probabilistic results. This can be understood by considering that the probabilistic technique spends a large portion of time accessing the disk and is fairly insensitive to the number of discrete control variables.

Figure 5-14 (b) shows the variation in the active losses against the number of discrete control variables. When a small number of discrete controls are included in the optimisation problem then the probabilistic technique, MINLP and KNITRO determine identical solutions. It is interesting to note that MINLP and KNITRO arrive at a solution quicker than the probabilistic technique for simpler problems involving a small number of discrete controls. As the number of discrete controls grow the probabilistic technique solution diverges from that of MINLP and KNITRO. These results demonstrate that the probabilistic technique is significantly faster, and determines a lower loss solution, when more than 13 discrete control variables are considered.

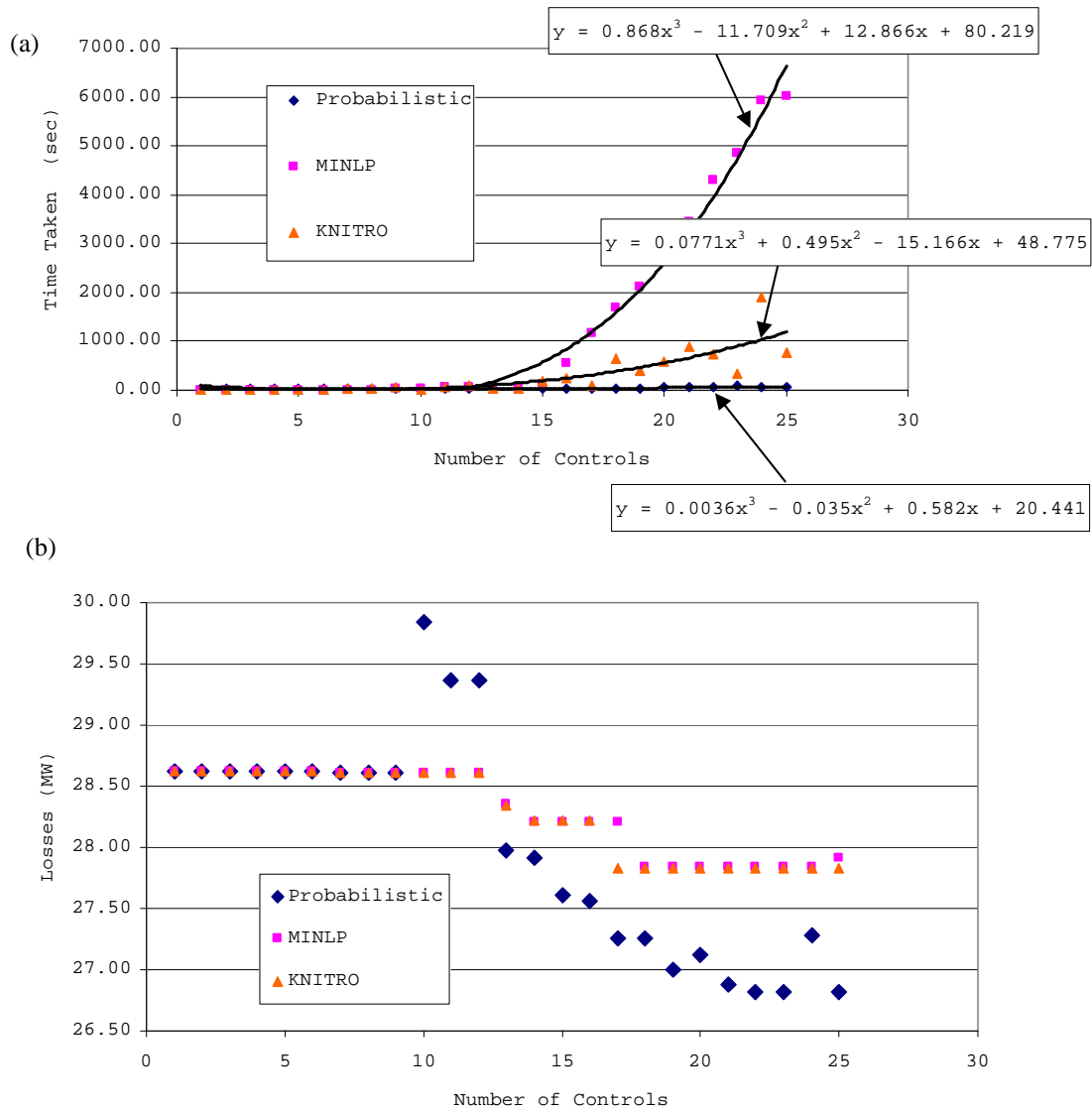


Figure 5-14. Comparison of probabilistic technique, MINLP and KNITRO variation with the number of discrete controls in the model. (a) Solution time, (b) active losses.

5.5.8 Comparison of large-scale GB network models

In Table 5-5 we considered four GB network studies that had been prepared by ENCC engineers to be representative of the transmission network at a particular time and date. The ORPF results shown in Table 5-9 present additional GB network studies distributed throughout the study year, these were intact network optimisation studies that were not constrained by contingency case events. Each GB network study was prepared using the procedure described in section 5.4.1. Shunt capacitors and reactors were set as initially switched out, as it was thought that this would help to distinguish the most effective optimisation technique. Each improvement value shown in Table 5-9 was determined by first calculating the

active losses reduction achieved with the standard ORPF rounding technique and then calculating the active losses reduction achieved with the proposed technique. The percentage improvement values could then be determined by comparing these loss reduction results.

Table 5-9 confirms that the probabilistic technique can provide additional active losses savings when solving mixed integer non-linear power system problems. The table demonstrates that the probabilistic technique is superior to the adaptive threshold technique for all network cases. The negative improvement values shown in the adaptive threshold column for networks representative of week 17 and week 23 indicate that the adaptive threshold technique actually reduced the active losses saving in these cases. The overall average improvement achieved by the adaptive threshold technique was 5.6% or 1.6% depending if the negative values are ignored or not. From Table 5-9 it can be seen that the adaptive threshold technique did not perform as well as the probabilistic technique, indicated by the large negative values in the third column of the table. This can be understood by considering the short-comings of the adaptive threshold technique. The adaptive technique will only discretise and fix particular shunt controls that have a solution that is inside the threshold, when no (or few) controls are fixed during an iteration then the optimisation solution will not change significantly. This means that the same controls will remain floating at the next iteration. Even when the threshold is widened then often only a few more shunts will be fixed, particularly if many have a solution half way between discrete step values. Effectively this means that the adaptive threshold technique can sometimes become stuck and produce little improvement.

Week Number	Percentage improvement in the objective relative to standard rounding approach	
	Probabilistic	Adaptive
9	18.00	12.30
11	8.19	5.63
13	3.68	3.55
17	7.70	-36.76
21	15.06	2.94
23	6.11	-0.39
24	14.81	10.97
27	3.96	0.69
32	1.25	3.07
36	4.88	0.76
37	22.58	13.96
40	0.15	2.03
Average Improvement (ignoring cases with negative improvement)	8.87	5.59

Table 5-9. Active losses reduction determined with the probabilistic and adaptive threshold techniques relative to initial GB network losses with a flat shunt switching pattern.

5.6 Enhanced Security Constrained Shunt Rounding Technique

5.6.1 Proposed enhancement technique

This section describes an enhancement to the published shunt rounding technique, which enables a large number of contingencies to be included in the practical optimisation problem. Macfie et al. [21] presented a probabilistic approach to extend existing SCORPF methods to effectively solve large-scale network problems involving discrete shunt devices. The enhanced technique proposed in this section is based on a modified version of this shunt rounding technique [112]. The network data is read and the main ORPF is performed assuming all controls are continuous, at this stage no contingencies constrain the optimisation. At every iteration a subset of the available floating shunt controls are fixed to their nearest discrete value. The probability of fixing is given by the closeness of a shunt's continuous solution to its nearest discrete value using the probabilistic approach described in section 5.3.2. This process is then repeated until a stop condition is satisfied when either the maximum number of iterations is reached or when all discrete controls are fixed. Any remaining floating discrete controls are then fixed to their nearest discrete value. Finally SCORPF is performed using only continuous controls to remove any contingency violations caused by the shunt rounding process. It is this final stage that ensures that the solution is secure against a range of contingencies.

5.6.2 Comparison of large-scale GB network models

The quoted active losses reduction values in this section are presented relative to the corresponding initial active losses with shunts set in their original manually configured position and with continuous control variables initialised at their corresponding optimal values. This differs with the approach that was used in section 5.4.2, which initialised all shunts as switched out, as it was realised that this was unnecessary. The quoted active losses reduction therefore represents the additional benefit of including the discrete shunt controls in the optimisation.

Figure 5-15 presents a comparison of the active loss reduction achieved by the two staged SCORPF standard rounding method and the proposed enhanced security constrained shunt rounding technique. The proposed technique has on average improved the percentage reduction in the losses reduction by an extra two thirds. If the extra improvement could be sustained over a full year of GB network operation then the additional losses energy saving would be equivalent to 26GWh, which has been calculated by assuming a 3MW average extra reduction in active power losses. The proposed technique has also managed to resolve a base case voltage violation and two contingency voltage violations that were present in the solutions from the traditional two staged SCORPF rounding technique.

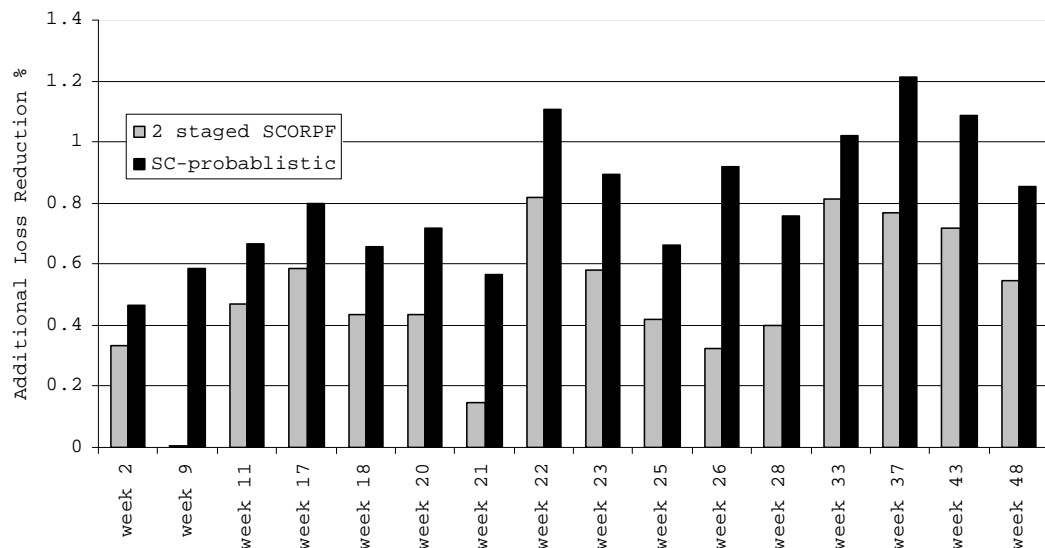


Figure 5-15. Comparison of the reduction in active transmission losses.

5.6.3 Relative solution time comparison

Figure 5-16 presents a comparison of the time taken by the proposed and standard techniques. The probabilistic solution of the GB4 network that is constrained with 40 contingency cases, which is shown in Table 5-5, took around one hour to converge on a solution. For comparison Figure 5-16 shows that the proposed enhanced technique is able to find a solution to GB network optimisation problems that are constrained with around 800 contingency cases in ten minutes. However, the figure also shows that the proposed technique has taken on average four minutes longer to converge on a solution than the standard technique.

This research utilised MATLAB to develop, execute and evaluate the probabilistic technique, this meant that external calls needed to be made to the SCORPF software. The author would therefore expect that an implementation of the technique directly within the optimisation software would significantly improve the performance due to the reduction in time spent accessing the disk.

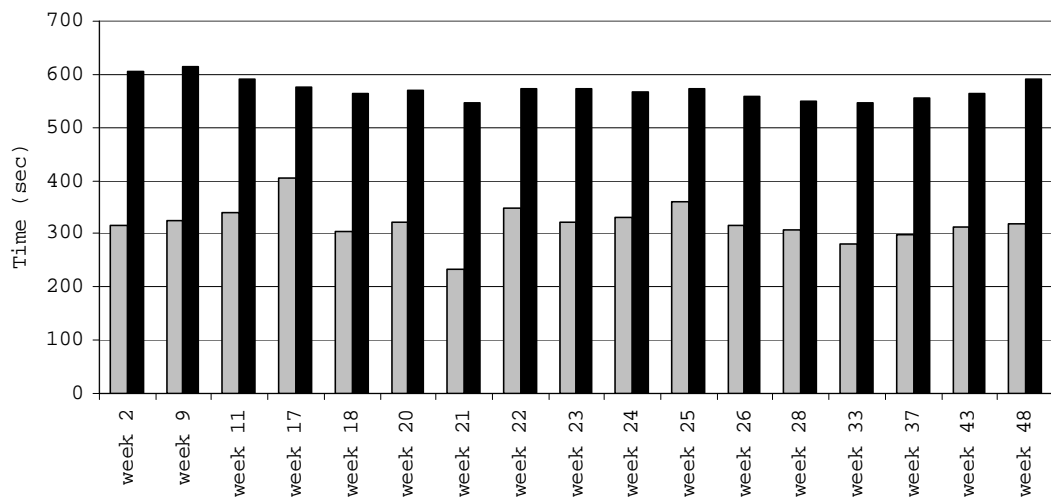


Figure 5-16. Comparison of the time taken. The same key is used as in Figure 5-15.

5.7 Summary

The standard technique that is usually applied by commercial SCORPF tools to generate a physical solution when discrete control variables are included in the optimisation is to round the discrete control variables to the nearest physical value at the end of the optimisation process. This rounding approach has been observed to cause both infeasibility and sub-optimality. A novel probabilistic and a novel

adaptive threshold technique were proposed in this chapter to solve this mixed integer network optimisation problem. The probabilistic technique consistently managed to produce a lower loss solution than the standard rounding technique for all test cases and achieved better results than the adaptive threshold technique.

The probabilistic technique was observed to scale significantly more efficiently than MINLP [104], KNITRO [106] and a penalty function based method developed by Liu, Tso and Cheng [101]. This is an important observation since it confirms that the probabilistic technique is the most suitable technique for solving large-scale SCORPF problems. Occasionally a solution generated by the probabilistic technique was observed to have lower active losses than the corresponding solution generated by the branch and bound based optimisation solver MINLP.

An enhanced version of the probabilistic technique was also described in this chapter to allow large-scale GB network SCORPF problems with around 800 contingency cases to be solved efficiently. The results from the proposed technique consistently achieved lower active losses than the standard rounding technique and sometimes managed to resolve limit violations that were not resolved with the standard technique.

The research presented in this chapter has been submitted by the author and accepted for publication in the peer reviewed journal, IEEE Transactions on Power Systems [21].

Chapter 6

Constraint Based Multi-Objective Optimisation

6.1 Introduction

Reactive power management of the GB transmission system is a complex multi-objective optimisation problem. At present human operators make reactive switching decisions, using their operational knowledge and experience, in order to achieve a compromise between different objectives. It has been widely recognized that there is an increasing need for automation in the operation of the GB transmission system [71], but this automation will require an effective method for handling multi-objectives. Therefore, this chapter considers techniques for modelling and optimising the reactive dispatch problem in a security constrained multi-objective formulation.

Chapter 4 demonstrated that the reactive utilisation volume and losses could simultaneously reduce when utilising a single Transmission Losses objective function. Therefore an effective method for handling multi-objectives is required and will be described in this chapter. Chapter 5 discussed the drawbacks of existing SC-ORPF for handling the mixed integer problem; this will also be relevant to the discussions within this chapter.

Previous studies have shown that optimisation techniques can be applied successfully to solve problems involving the GB transmission network model [13, 18]. These studies did not adequately tackle the multi-objective nature of the optimisation problem. A novel technique and a standard technique are compared in this chapter to address this operational multi-objective problem of determining the appropriate dispatch of reactive controls to reduce active transmission losses with a simultaneously reduction in the generator reactive utilisation. These techniques are demonstrated using four standard IEEE network models and 26 large-scale practical networks. All large-scale studies were performed on GB

transmission network planning models and complied with the National Electricity Transmission System Security and Quality of Supply Standards (SQSS) [3], with each large-scale network optimisation considering approximately 800 credible contingency cases.

The ‘Pareto Curve’ is a term from optimisation theory. It is used in contexts where more than one objective function is simultaneously minimised and represents a trade-off curve. In general it can be thought of as the set points in a parameter space where one objective function cannot be reduced without raising another. It therefore represents a set of compromise solutions to the multi-objective optimisation problem [31].

The standard technique for solving multi-objective power system optimisation problems is to form a weighted sum combination of the individual objectives [81, 83, 84]. It is well known that this technique can only find all points on the Pareto Curve when the Pareto Curve is convex. Secondly it has been frequently observed that an even distribution of weights fails to produce an even distribution from all parts of the Pareto Curve [30]. The large-scale security constrained reactive optimisation problem is non-linear and non-convex, so both of these phenomena are possible. These pitfalls would make a practical multi-objective optimisation tool, which is based on the standard weighted sums technique, unreliable since it is impossible to know the correct weights needed to evenly generate points on a Pareto Curve without actually knowing the shape of the Pareto Curve in advance. For example minimising an equally weighted sum of objectives is unlikely to result in a solution that is in the middle region of the Pareto Curve.

A practical multi-objective reactive optimisation technique is therefore required to generate a more uniform set of Pareto points and achieve more consistent results across a range of network studies. The constraint-based technique described in this chapter is based on the idea of applying additional fictitious soft constraints to the reactive power flow across generator transformers to limit the pre-fault generator reactive utilisation of each generator [20]. The constraint-based technique was initially deployed to prevent the generator reactive utilisation from increasing when the active transmission losses minimisation problem was solved,

however it was later realised that the technique could also be used effectively to reduce generator reactive utilisation. The constraint-based technique is easily integrated into existing SCORPF software and is relatively transparent in its operation. This chapter presents results showing that an improvement has been achieved using the constraint-based technique. This chapter assumes that the cost of each leading or lagging MVar is identical, because the vast majority of generators are paid at the default reactive price [70]. This assumption means that a reactive costs minimisation objective becomes a generator reactive utilisation minimisation objective since all costs are identical. Hence this chapter considers SCORPF with a multi objective consisting of active losses and generator reactive utilisation.

The final section of this chapter presents a comparison of the results from SCORPF using the constraint-based technique on a selection of network studies that were prepared by ENCC engineers [20].

6.2 Standard Multi-objective Technique

Multi-objective optimisation problems are often formulated as convex weighted combinations of the different objectives. The multi-objective function composed of n separable objectives $f(x)$ can be written as:

$$\min_x \sum_{i=1}^n w_i f_i(x) \quad (6-1)$$

where the weighting values w_i are chosen such that $w_i > 0$, $i=1 \dots n$ and $\sum w_i = 1$. The optimisation is solved subject to the required equality and inequality constraints. x represents a vector of variables in the optimisation.

A common approach is to perform the minimisation of the multi-objective shown in the equation above with an even spread of weights with the aim of generating a spread of points on the Pareto Curve. Das and Dennis [30] identified two problems that are often encountered with the weighted sums approach:

- If the Pareto Curve is not convex then some regions of the curve will not be accessible.

- Even for a convex Pareto Curve an even spread of weights w does not necessarily produce an even spread of points on the Pareto Curve.

This chapter considers the minimisation of the active transmission losses and the generator reactive utilisation objectives, and is therefore a multi-objective optimisation problem with two weighted objectives. The standard weighting technique formulates the optimisation in the form shown in equation 6-1 [30].

$$\min_x (1-\alpha)f_1(x) + \alpha f_2(x) \quad (6-2)$$

α is a scalar that can vary between 0 to 1. $f_1(x)$ represents the active transmission losses objective function and $f_2(x)$ represents the generator reactive utilisation objective function.

$$\alpha = \frac{\sin \theta}{\cos \theta + \sin \theta} \quad (6-3)$$

Now substitute α from equation 6-3 into equation 6-2 to give equation 6-4.

$$\min_x \frac{\cos \theta}{\cos \theta + \sin \theta} f_1(x) + \frac{\sin \theta}{\cos \theta + \sin \theta} f_2(x) \quad (6-4)$$

θ varies from 0 to $\pi/2$.

A Pareto point is a solution of equation 6-2 for some value of α , if and only if it is also a solution of equation 6-4 for some value of θ [30]. If a Pareto point is not a solution of equation 6-4 for any value of θ then it cannot be obtained by minimising any convex combination of equation 6-2.

To understand this consider an anti-clockwise rotation of the $f_1(x)$ - $f_2(x)$ axis shown in Figure 6-1 by an angle θ . The new axis is $f_1'(x)$ - $f_2'(x)$. The coordinate transformation is given by [30]:

$$\begin{bmatrix} f_1'(x) \\ f_2'(x) \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} f_1(x) \\ f_2(x) \end{bmatrix} \quad (6-5)$$

$$f_1'(x) = f_1(x) \cos \theta + f_2(x) \sin \theta \quad (6-6)$$

Divide equation 6-6 by $(\cos \theta + \sin \theta)$ to get equation 6-4. Therefore a minimisation of $f_1'(x)$ wrt x is equivalent to the minimisation shown in equation 6-

4. Therefore if a region of the Pareto Curve is hidden to a minimisation over all axis rotations then a region of the Pareto Curve will also be hidden to a minimisation of equation 6-2 over all values of α [30].

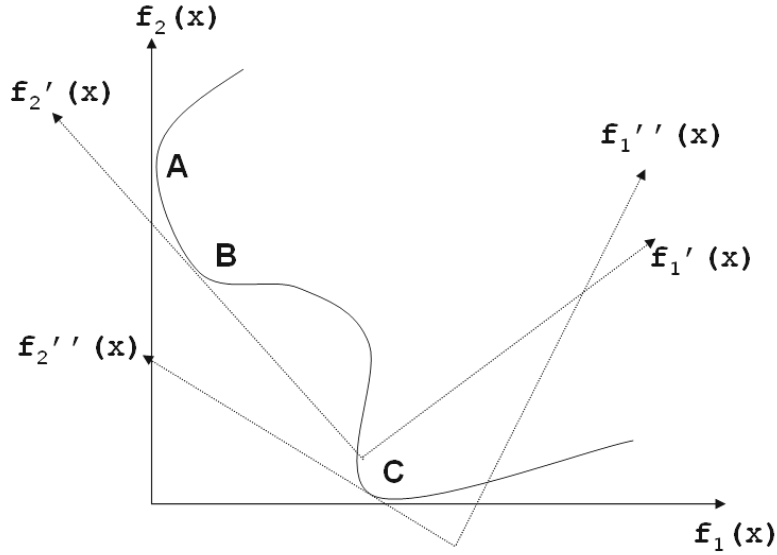


Figure 6-1. Non-convex parts of the Pareto Curve are not captured for any value of θ in equation 6-4.

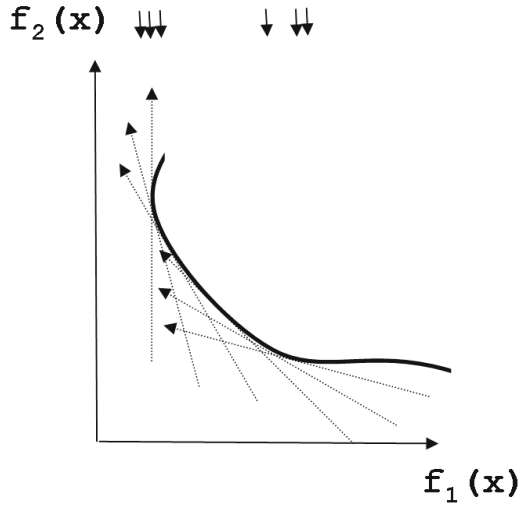


Figure 6-2. Non-uniform distribution of Pareto points on the Pareto Curve as θ in equation 6-4 is increased in steps of $1/12\pi$.

Figure 6-1 shows the solution obtained by minimising $f_1(x)$ to obtain point A on the Pareto Curve. Figure 6-1 also shows a rotation to a new axis $f_1'(x)$ - $f_2'(x)$ and the minimisation of $f_1'(x)$, to obtain B. Now imagine a further rotation to a new axis $f_1''(x)$ - $f_2''(x)$ and then minimisation of $f_1''(x)$. The solution will jump to point C on the Pareto Curve. Figure 6-1 visually reveals that some parts of the Pareto

Curve will always remain hidden to the searching process for all axis rotations from 0 to $\pi/2$. This hidden part of the Pareto Curve can cause problems for multi-objective optimisation as it can cause discontinuities in the value of the objective function.

For the non-convex Pareto Curve shown in Figure 6-1, as θ is gradually increased, the weighting technique will not give an even spread of Pareto points on the Pareto Curve. Das and Dennis [30] argue that even a convex Pareto Curve does not guarantee that the weighting technique will generate a uniform spread of Pareto points. This is illustrated in Figure 6-2 where θ is gradually increased in steps of $1/12\pi$. The arrows at the top of the figure indicate the position of the points on the Pareto Curve determined using the standard weighting technique. Das and Dennis state that ‘In many cases it has in fact been observed that the points obtained using a uniformly spread set of values are actually clumped in certain regions of the Pareto set, providing the user no information about the nature of trade-off between the two objectives’. This could cause a significant issue when using the weighting technique to solve the multi-objective power system optimisation problem, because it maybe impossible to generate an even spread of objective function values without knowing the shape of the Pareto Curve in advance.

The method of performing the optimisation using a weighted multiple objective function, which was described in this section, will be referred to as the weighting technique for the remainder of this chapter.

6.3 Novel Multi-objective Technique

The constraint-based technique described in this section is based on the idea of applying additional fictitious soft constraints to the reactive flow across generator transformers in order to limit the pre-fault reactive utilisation of each generator. The standard losses minimisation problem is then solved with these additional constraints in order to achieve a solution which considers the minimisation of both generator reactive utilisation and active losses. The magnitude of each reactive flow constraint included in the optimisation is based on the initial generator

transformer reactive power flow multiplied by a value that can vary from zero to infinity to give the desired balance between generator reactive utilisation minimisation and active losses minimisation respectively, this value shall be referred to as the multiplier for the remainder of this chapter. This multiplier represents a trade-off parameter between transmission losses and reactive utilisation reduction. Figure 6-3 illustrates an example of three generator transformers, which control a single optimisable HV bus bar voltage to a target value, with an LV side connected to a generator. The constraint-based multi-objective technique includes a reactive flow constraint for each modelled generator transformers that is controlling an optimisable HV bus target voltage. The upper constraint limit on reactive flow across eligible transformer branches is given by the following formula:

$$QFlow_{constraint} = QFlow_{initial} * multiplier \quad (6-7)$$

$QFlow_{initial}$ refers to the generator transformer reactive power flow before optimisation and multiplier is a user-defined value that can vary from 0 to infinity. The lower constraint limit on the reactive flow is the negative value of equation 6-7. The optimisation then proceeds with these additional constraints while considering only the active transmission losses minimisation objective.

The method of performing the optimisation using the active transmission losses minimisation objective with the extra branch reactive flow constraints will be referred to as the constraint-based technique for the remainder of this chapter.

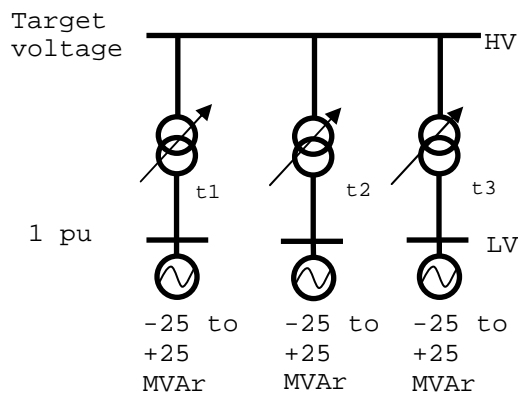


Figure 6-3. Generator transformer modelling.

With a multiplier less than 1.0 it is possible that the optimisation problem is infeasible. Therefore it is important to include some infeasibility logic to alter the problem that we are trying to solve [33]. One strategy suggested by Stott and Hobson is to gradually increase some line limits by a percentage and then resolve. By repeatedly increasing the line limit a feasible solution should eventually be generated.

The following example describes the effect of applying additional branch flow constraints to the optimisation. Consider a network with a generator transformer reactive power flow initially equal to 100 MVar. After optimisation to minimise losses, the flow may increase, resulting in a more expensive solution. It would therefore be desirable to place a limit of 100 MVar on the flow (multiplier=1.0). The optimised solution should now achieve a solution with a flow of 100MVar or less. Next consider the same optimisation with a limit of 50MVar (multiplier=0.5), the solution should achieve a smaller flow than that present in the initial network. If a limit of 0 MVar is applied then the solution would usually have the smallest reactive flow value (multiplier=0.0). However, in the later scenario it is likely that constraint softness would need to be applied during the optimisation in order to avoid the problem being infeasible.

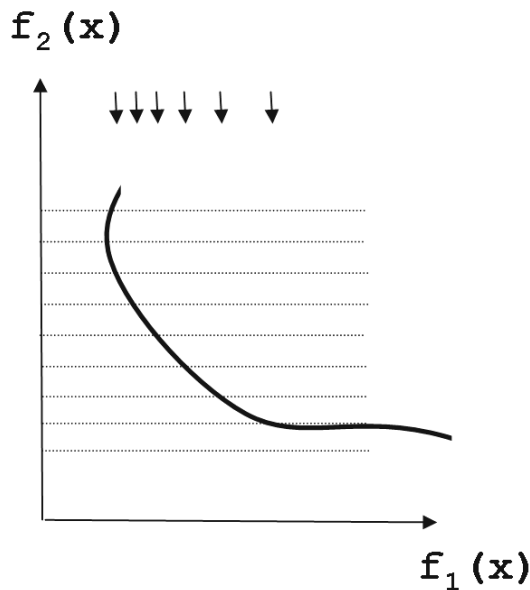


Figure 6-4. Distribution of Pareto points on the Pareto Curve calculated by minimising $f_1(x)$ with an upper limit constraint placed on $f_2(x)$ indicated by the horizontal dotted lines.

Figure 6-4 geometrically illustrates how the branch constraint technique can be used to determine points along the Pareto Curve. The curve, which is the same as that shown in Figure 6-2, can be considered to represent a very simple power network with just one generator being considered in the reactive utilisation summation represented by $f_2(x)$. The total network active losses is represented by $f_1(x)$. The dotted horizontal lines indicate an upper limit constraint placed on the generator reactive utilisation for each optimisation of active transmission losses. The arrows at the top of the figure indicate the position of each solution on the Pareto Curve.

An advantage of the constraint-based technique can be understood by a comparison of Figure 6-2 to Figure 6-4, which indicates that the constraint-based technique is able to determine a more uniform distribution of Pareto points than the weighting technique. It is possible to conceive of a Pareto Curve that would be represented better using the weighting technique. However for Pareto Curves with regions of low curvature, the constraint-based technique may be able to achieve better results in practice. Unlike the weighting technique the constraint-based technique does not require a set of fixed weightings to be determined in advance. The constraint-based technique determines the constraints to be applied in the optimisation directly from the network that is being optimised.

6.4 Single Objective Improvement using Constraint-Based Method

This section describes how the constraint-based technique, which includes additional generator transformer reactive flow constraints in the optimisation, superseded a technique that was implemented in the previous version of the SCOPE optimisation software when solving the single objective problem involving the minimisation of generator reactive utilisation.

A GB offline network was prepared in the required format to represent Monday 25th May 2009 at mid-day using the method described by Macfie et al. [19]. Power flow was solved for the initial network to determine the active losses and the generator reactive utilisation. The generator reactive utilisation was

determined by summing the absolute values of all the reactive generator outputs. Optimisation was then solved with either the active losses or the generator reactive utilisation minimisation objectives. Optimisation was also solved with additional generator transformer reactive flow constraints with different values of the multiplier.

Table 6-1 demonstrates that the inclusion of generator transformer reactive flow constraints can greatly enhance the intact network optimisation results in terms of both the final optimised active losses and generator reactive utilisation. The table shows results from the previous version of SCOPE (version 12.1) and compares them with and without the extra constraints. Optimisation using the active losses objective function on its own caused an increase in generator reactive utilisation, with the extra constraints the optimisation managed a further improvement in the losses reduction and a significant reduction in generator reactive utilisation. This result is surprising and would seem to indicate that constraining the optimisation can sometimes improve the solution.

Optimisation using the generator reactive utilisation minimisation objective on its own without any additional constraints achieved a 7% reduction in generator reactive utilisation, but with the extra constraints the optimisation managed to achieve a 75% reduction in generator reactive utilisation with an accompanying reduction in losses.

Optimisation Objective	Branch Constraint Multiplier	Losses (MW)	Q-Volume (MVAR)
Initial network	N/A	708.04	5116
Losses	No extra constraints	693.62	6063.6
Losses	1	686.87	3037.6
Losses	0.7	687.55	2686
Losses	0.5	693.06	2407.7
Q-Utilisation	No extra constraints	708.77	4763.3
Q-Utilisation	1	717.32	4374.3
Q-Utilisation	0.7	710.09	3458.2
Q-Utilisation	0.5	700.56	1260.1

Table 6-1. Compares ORPF results from the active losses and the reactive utilisation objective functions with no extra constraints and with extra branch reactive flow constraints.

The extra improvement observed in the generator reactive utilisation minimisation objective is counter intuitive, because the generator reactive utilisation

minimisation objective should find the minimum solution and additional constraints should cause the solution to become more expensive. It was eventually determined that the way in which the generator reactive utilisation minimisation objective was being formulated was not suitable for the GB network. This issue arose because the GB transmission network has fewer voltage controls than typical US transmission networks. The software has now been updated and now uses a technique based on the one described in this chapter to find the correct value of the generator reactive utilisation. The results given in the remainder of this chapter are obtained using SCOPE version 12.2, which now determines superior solutions to those presented in Table 6-1.

6.5 Small Scale Network Results

6.5.1 Introduction

This section presents a multi-objective optimisation investigation involving a comparison between ORPF solutions determined using the weighting technique and the constraint-based technique. The 14-bus, 30-bus, 57-bus and 118-bus standard IEEE networks are investigated with minor modifications made to each network. A wide range of weighting values and multiplier values are investigated corresponding to the weighting technique and constraint-based technique respectively. This section begins with an overview of the data preparation process, this is followed by a description of how the optimisation was structured and finally the results are discussed.

All generators in each IEEE network were disconnected from their local bus and reconnected to a dummy bus. These dummy buses were then connected by a dummy branch back to the original generator bus. Each generator was modelled to control its local dummy bus to within a target voltage. These controls were then flagged as optimisable within the model. This model reconfiguration allowed branch flow constraints to be specified for each generator connected branch in the model and therefore allowed the application of the constraint-based technique. Branch flow constraints were only included in the model for branches with a reactive flow of more than 1.0 MVar flow in order to avoid constraints being

specified in the optimisation that were very close to zero. The model was then populated with uniform reactive cost data to allow the application of the weighting technique. These metered reactive power costs (£/MVARhr) were assigned at the generator side of each of the dummy branches and therefore the optimisation was solving the generator reactive utilisation minimisation problem.

The first part of the investigation involved solving ORPF on the IEEE test cases using the linear weighted sums multi-objective function. This objective was given in equation 6-2, but is rewritten here in a modified form:

$$Objective(x) = W_L * Losses(x) + W_C * Utilisation(x) \quad (6-8)$$

W_L is the weighting value on the active losses and W_C is the weighting value on the generator reactive utilisation. At this stage no additional branch reactive flow constraints were placed on the generator branches. Each network was investigated using different values of W_L keeping W_C constant at a value of unity. The optimisation was typically repeated with values of W_L ranging from 0 to 2000 in steps of 100. W_L will be referred to as the weighting for the remainder of this chapter, since the other weightings remain fixed.

The second part of the investigation used the same network models and optimisation settings, but only included active transmission losses in the objective function. Branch reactive flow constraints were now included for each branch connecting to a generator, the magnitude of which was based on the initial power solution and determined by using equation 6-7. The optimisation was repeated with different values of the multiplier ranging from 0 to 1.2 in steps of 0.05. This meant that prior to running each optimisation the branch constraint data needed to be updated.

After each optimisation the active power losses and generator reactive utilisation was calculated and stored. The generator reactive utilisation was determined by summing the absolute values of all the reactive generator outputs. Solution violations and convergence reports were also recorded.

6.5.2 Results

The 14 bus IEEE network was investigated using the constraint-based and weighting multi-objective techniques. The active transmission losses and generator reactive utilisation was found to be insensitive to the applied weighting or multiplier values. This implies that the solution to the active losses optimisation and generator reactive utilisation optimisation were very similar. Therefore the 14 bus network was determined not to be useful for comparing the constraint-based and weighting approaches, but did demonstrate that there was some agreement.

Figure 6-5 presents 30 bus IEEE network results from both the weighting and constraint-based technique investigations. Figure 6-5a shows the variation in the measured active losses and the generator reactive utilisation as the weighting W_L is increased from a value of 0 to 2000 using the weighting technique. Figure 6-5b shows results obtained as the multiplier on the branch constraints is increased from 0 to 1.2 using the constraint-based technique.

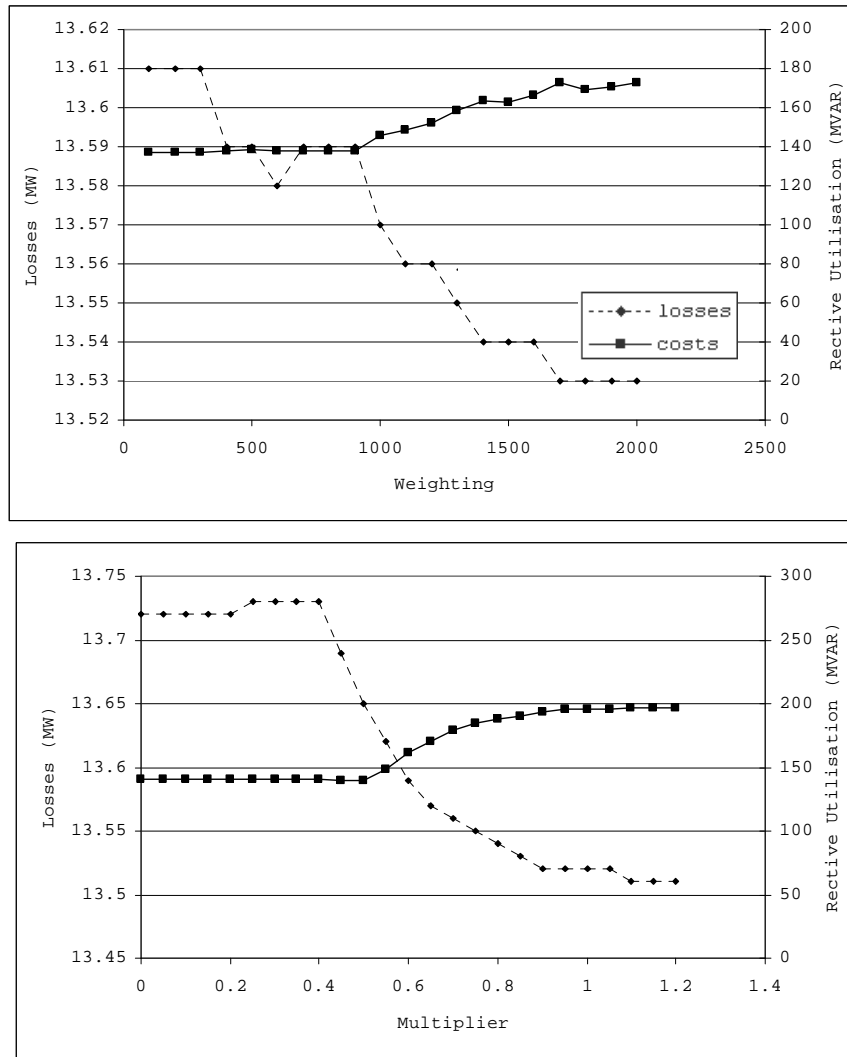


Figure 6-5. 30 bus multi-objective results. (a) Weighting technique results and (b) Constraint-based technique results.

The results from the 57 bus IEEE network are shown in Figure 6-6. As described in the introduction section, one of the drawbacks with the weighting technique is the problem of deciding the appropriate range of weighting values to apply in order to capture the sensitive part of the Pareto Curve. This issue is demonstrated by the insensitivity to the range of applied weighting values in Figure 6-6a. Therefore a smaller range of weighting values, from 0 to 200, needed to be investigated and is shown in Figure 6-6b.

Figure 6-7 presents similar results for the 118 bus IEEE network. Figure 6-8 presents Pareto optimality curves determined from the IEEE standard network results. These curves were obtained by plotting the optimised values of the active losses against the generator reactive utilisation.

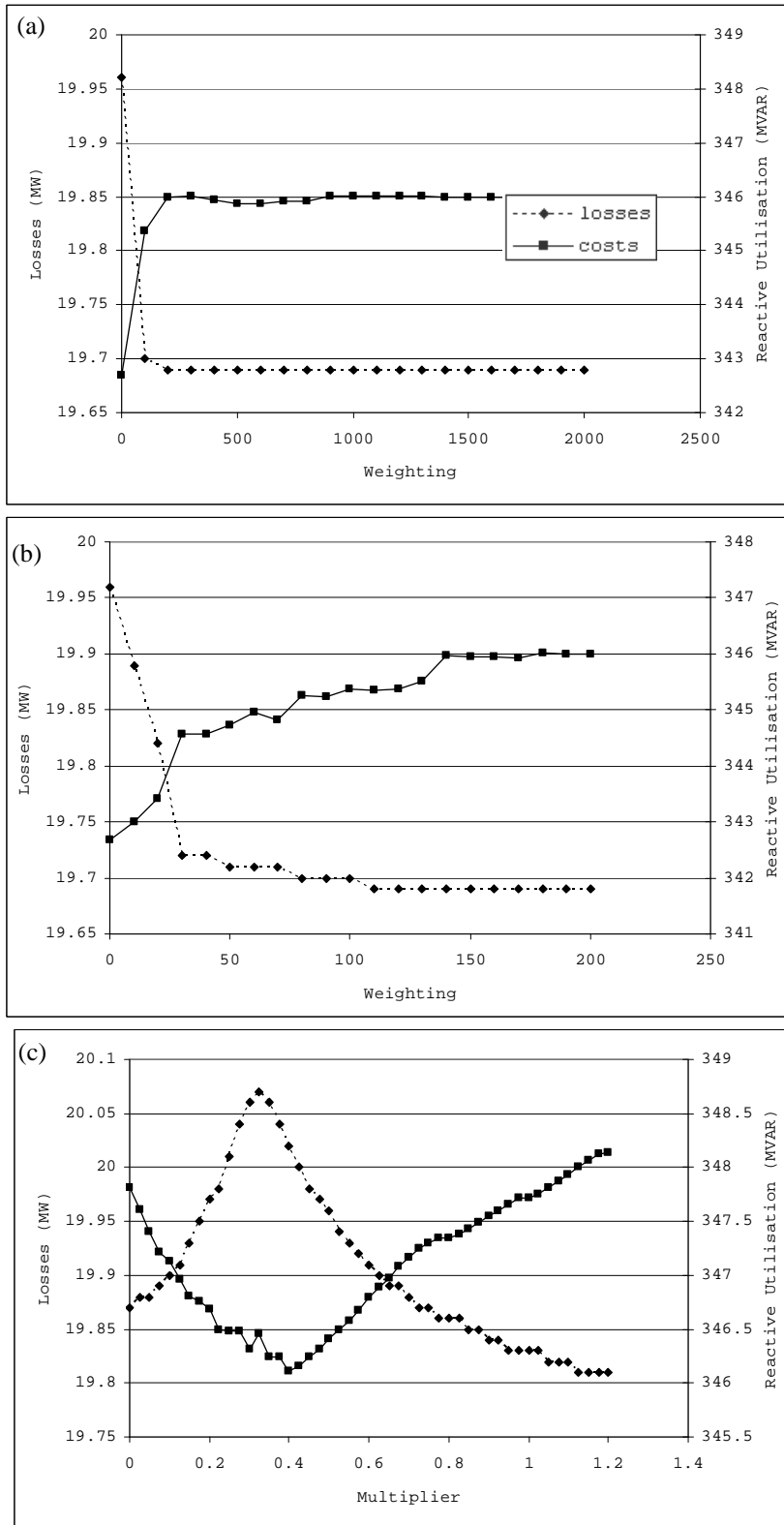


Figure 6-6. 57 Bus multi-objective results. (a) weighting investigation results over W_L range 0 to 2500 (b) W_L range 0 to 250 (c) Constraint-based investigation

Multiplier	Number of branch limit constraints that have gone soft	Sum of reactive flow for all branches with soft limit constraints
0	3	118.3
0.1	3	117.7
0.2	3	117.3
0.3	3	117.1
0.4	2	49.3
0.5	2	55.9
0.6	2	61.7
0.7	2	70.1
0.8	1	24.9
0.9	1	27.4
1	1	28.9

Table 6-2. Shows how the constraint relaxation logic changes the behaviour of the optimisation when a constraint multiplier of less than 0.4 is applied.

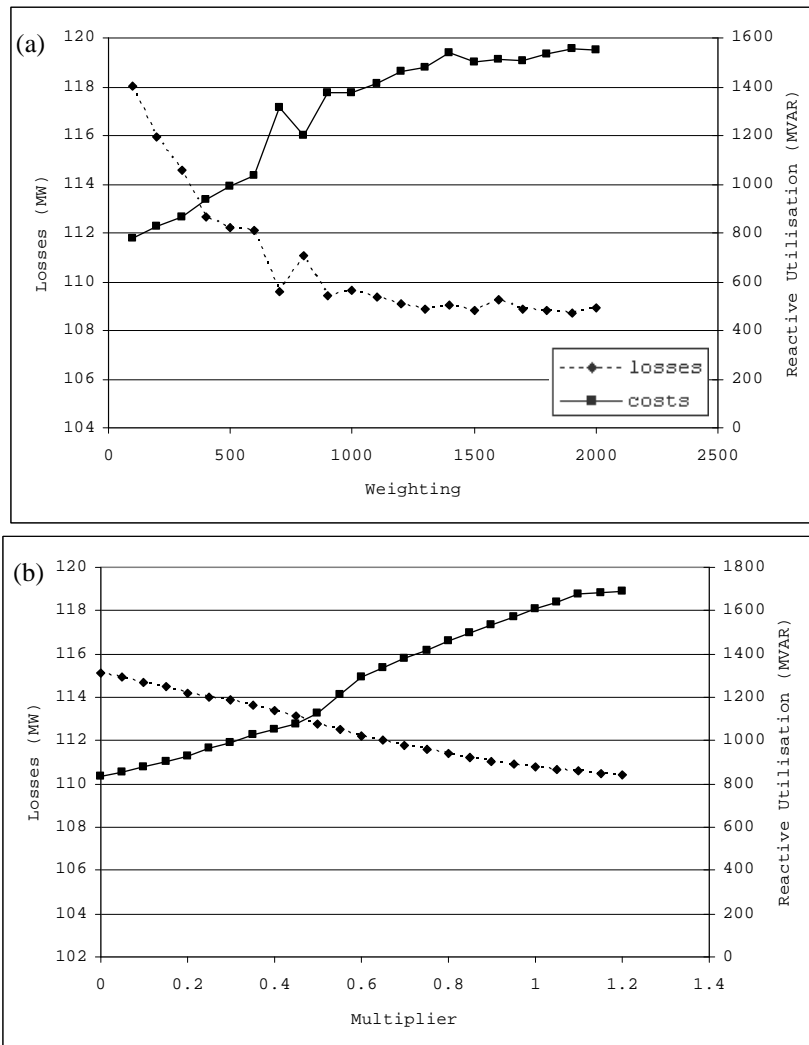


Figure 6-7. 118 bus multi-objective results. (a) Weighting technique investigation results and (b) constraint-based technique investigation results.

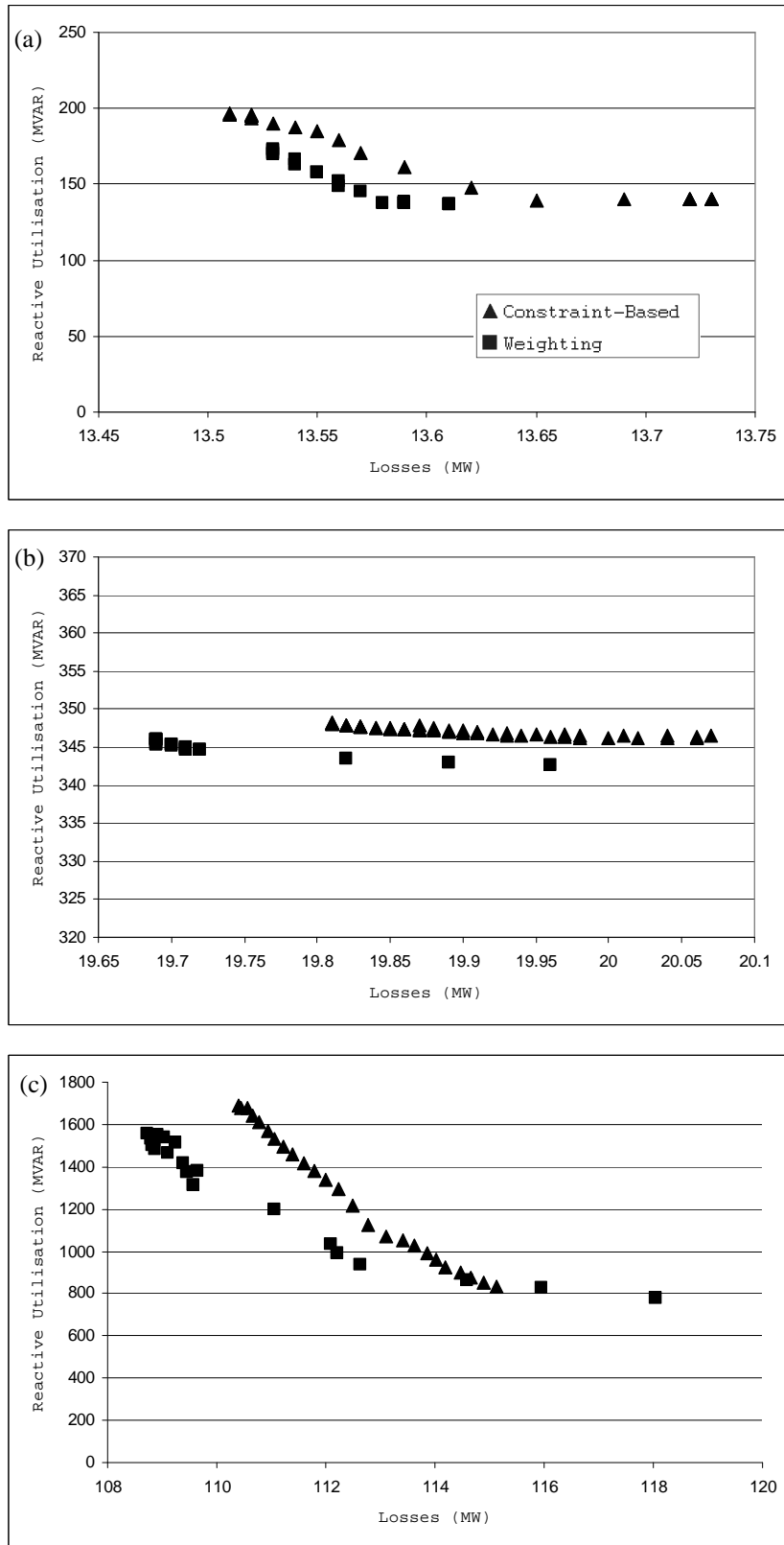


Figure 6-8. Active losses objective against the reactive costs objective Pareto optimality points. (a) 30 bus results (b) 57 bus results (c) 118 bus results

6.5.3 Discussion

Figures 6-5 to Figure 6-8 visually illustrate the advantages and disadvantages of the weighting technique and the constraint-based technique on a range of standard test networks. Figure 6-6b shows that it is difficult to determine in advance a sensitive range of weighting values to investigate the Pareto Curve when using the weighting technique. The weighting technique results shown in the other figures confirm this insensitivity over some parts of the investigated range. These results also demonstrate that the objective function values do not vary smoothly as the weighting value is modified. Figure 6-6c indicates that the constraint-based technique does not have this issue, which uses the same range of values as those applied to the other networks. Figure 6-6c also indicates that the constraint-based technique is exhibiting some anomalous behaviour for multiplier's less than 0.4 on the IEEE 57 bus network. A further investigation, presented in Table 6-2, reveals that this behaviour is due to the way the optimisation is handling soft constraint limits. As a constraint on a variable, which has already gone soft, is reduced the optimisation should find a solution for the respective variable that is smaller. Table 6-2 confirms this behaviour for multiplier's of 0.4 to 0.7 when there are two soft constraints, and also for multiplier's of 0.7 to 1.0 when there is just one soft constraint. This behaviour is not observed for multiplier's less than 0.4, which indicates that the action of the constraint relaxation logic is different. The results, shown in Figures 6-5 and 6-7, from the constraint-based technique obtained using the other IEEE networks do not have this issue. Figures 6-5, 6-6 and 6-7 indicate that the constraint-based technique manages to produce smoothly varying results.

The family of Pareto Curves shown in Figure 6-8 illustrate that both the weighting and constraint-based techniques have managed to produce curves with the expected shape; however in some cases the weighting technique has found lower objective function values. The weighting technique formulates the objective function in terms of the generator reactive utilisation minimisation objective, which is itself solved using a constraint based technique (see section 6.3). It therefore seems reasonable that the reduced objective function values observed in

the results from the weighting technique are achieved by a more efficient implementation of the constraint based approach directly in the SCOPE software.

The insensitive and unpredictable behaviour of the weighting technique, seen in figures 6-5 to 6-7, has practical implications when solving the multi-objective ENCC optimisation problem of minimising a combination of active transmission losses and generator reactive utilisation. The optimisation should be able to produce a predictable and consistent reduction in the objective function as the weighting value is modified. Figures 6-5 to 6-7 demonstrate that the constraint-based technique has managed to achieve this consistency, as a more predictable behaviour is observed over the range of tested multiplier values.

6.6 GB Network Results

6.6.1 Introduction

The main application for the constraint-based technique is for solving multi-objective SCORPF problems involving the large-scale GB network model. This section presents results that will be crucial in the development of a practical voltage optimisation tool that minimises a combination of the active losses and generator reactive utilisation minimisation objectives.

A rigorous comparison of the weighting technique and constraint-based technique was carried out, which involved testing 26 large-scale offline GB networks representative of snapshots throughout the year spread over a mixture of day-time and night-time networks. The investigation method utilised an adapted version of the Ella Voltage Optimisation Tool (EVOT) that will be described in the next chapter and is summarised below.

Data was converted from National Grid's in-house ELLA format to the SCORPF format and optimisation modelling data was added. The modelled control variables within the SCORPF included:

- Generator voltage targets.
- SVC voltage targets (all SVCs are in voltage target mode)

- Discrete shunt capacitors in/out of service.
- Discrete shunt reactors in/out of service.

The modelled system constraints included [17]:

- Control limits (e.g. generator, and SVCs).
- MVar interchange between user defined reactive power areas.
- Voltage limits.
- Voltage step-change limits.
- Generator MVar reserves – relaxed for contingency cases.

Before running the main optimisation process extra data was modelled so that a comparison could be made between the weighting technique and the constraint-based technique. The model was populated with uniform reactive cost data to allow the application of the weighting technique using a process similar to that described in section 6.2. The model was also populated with generator reactive flow limit constraints using equation 6-7, in order to allow the application of the constraint-based technique. While investigating the weighting technique the reactive flow constraints were excluded from the optimisation.

Around 800 credible double circuit and single circuit contingencies were included in order to ensure that the results from the optimisation were realistic and useful. Contingencies that were not credible were excluded from the optimisation by filtering those that were violated or non-convergent in the initial input network that had been prepared by ENCC engineers. SCORPF using the constraint-based technique was performed with multiplier values from 0 to 1.2 in steps of 0.05, and SCORPF using the weighting technique was performed with losses weighting values from 0 to 2000 in steps of 100. Therefore a total of 1196 optimisations were carried out ($21 \times 26 + 25 \times 26$). The completion time of each optimisation was typically around five minutes. The following metrics were recorded for each and every optimisation:

- active losses reduction %
- reactive cost reduction %
- time taken (sec)
- number of optimised intact network voltage violations
- number of optimised contingency case voltage violations

6.6.2 Results categorised into daytime and night time network studies

Obtaining these SCORPF results on large networks involved collecting a large quantity of data, therefore a systematic method was utilised to process the data into a visual form. The average reduction in active losses and generator reactive utilisation over the eight night time networks and the eighteen daytime networks was determined for each weighting value or multiplier value that was investigated. The standard deviation in the results was also recorded. In this section results are presented as a percentage rather than as an absolute value, which means that larger values relate to an improved objective function value.

Figure 6-9 presents the weighting technique investigation results on 32 large networks. This figure shows the active losses reduction % against the W_L weighting value and also shows the generator reactive utilisation reduction % against the W_L weighting value. The range of weighting values applied to these large network SCORPF studies was the same as that used for most of the small network investigations with a range chosen in such a way as to capture a sensitive region of Pareto Curve.

ENCC engineers have highlighted a difficulty with achieving a desirable voltage profile at night, when it is important to keep the voltage low in order to avoid a run-away increase. Therefore the results have been categorised into daytime and night time network studies.

Figure 6-9 shows that the weighting technique has generally managed to achieve a bigger reduction in active losses as the losses weighting is increased. However, as the weighting is increased the losses reduction did not increase smoothly. Conversely as the weighting on losses is reduced, and the ratio of the generator reactive utilisation weighting to the losses weighting gets bigger, the optimisation manages to generally reduce the generator reactive utilisation. Figure 6-9 shows that different portions of the investigated range have different sensitivities to the changing value of the weighting. The relationship between the losses reduction

and the weighting value was different for the daytime and night time network studies, but the behaviour in terms of the reactive reduction was similar.

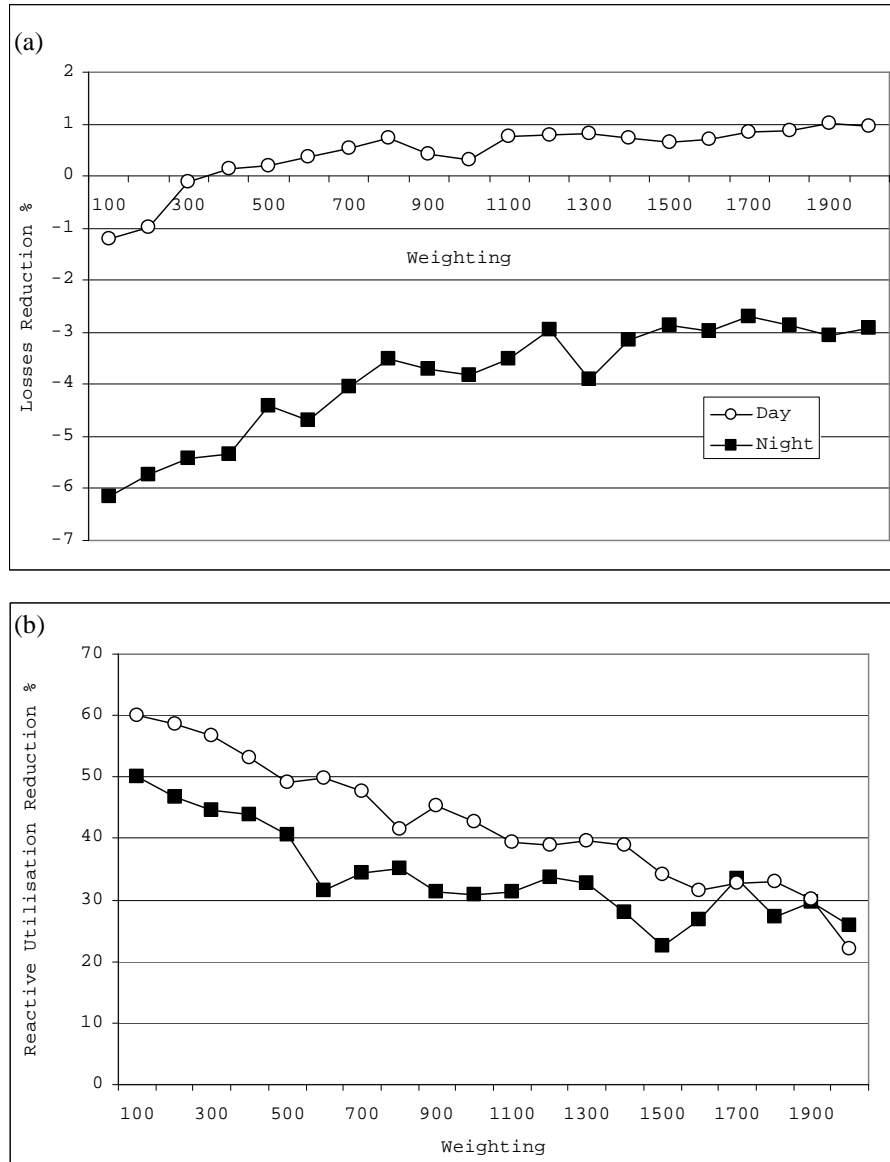


Figure 6-9. SCORPF results using weighting technique. (a) Active losses reduction %, (b) reactive utilisation saving %.

Figure 6-10 presents the constraint-based technique's investigation results over the same range of multiplier values as that used to investigate the smaller IEEE networks. Figure 6-10 indicates that the constraint-based technique has managed to achieve a consistent solution for the large-scale SCORPF studies on day time networks, such that the generator reactive utilisation reduction increases smoothly as the multiplier value on the constraints is reduced. The losses reduction is seen to generally increase as the value of the multiplier is increased. The results from the night time network did not show such a smooth behaviour, but did exhibit a

more desirable characteristic than that seen in Figure 6-9 since positive losses reduction was achieved and a greater improvement range could be accessed.

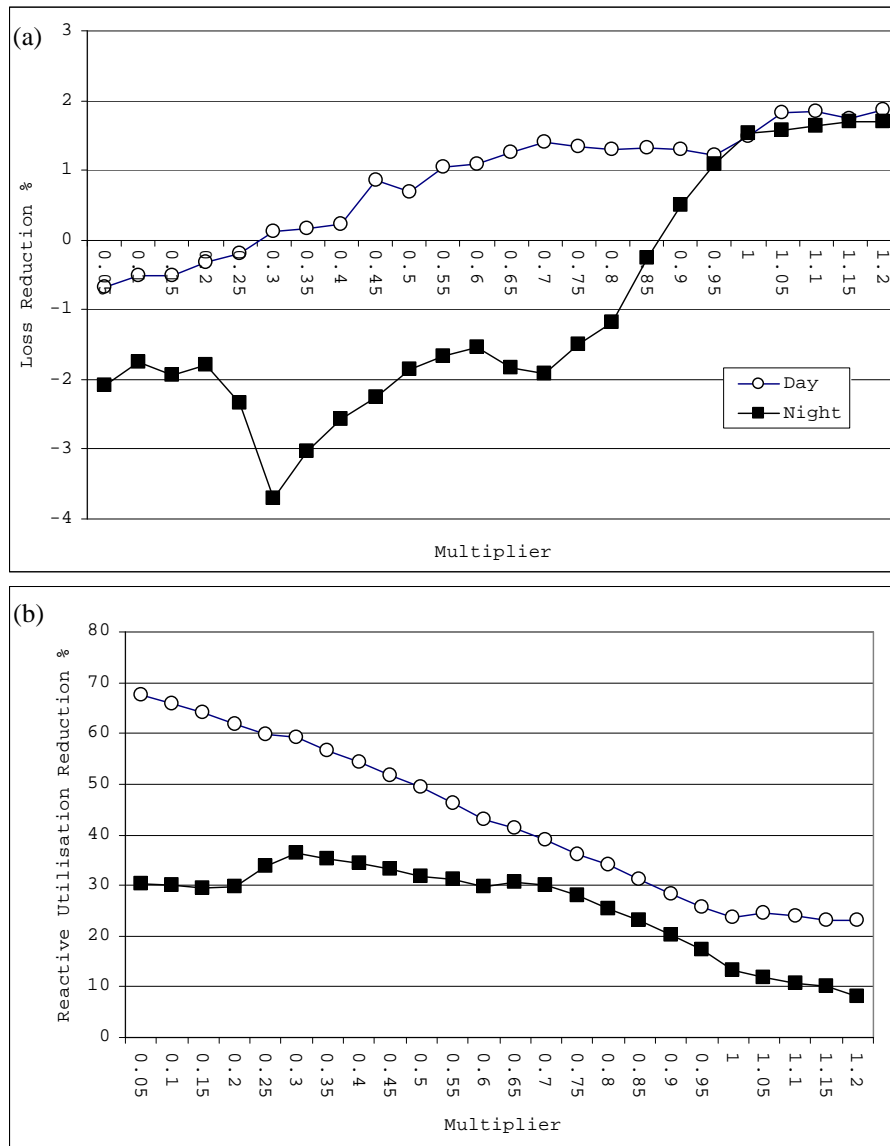


Figure 6-10. SCORPF results using constraint-based technique. (a) Active losses reduction %, (b) reactive utilisation saving %.

6.6.3 Overlay of the weighting and constraint-based results

An alternative presentation of the results is shown in Figure 6-11, which overlays the results from the weighting and constraint-based techniques. The results presented in this figure are averaged over all 26 networks rather than being categorised into daytime and night-time network studies.

Figure 6-11 highlights some important practical benefits of utilising the constraint-based technique over the weighting technique. These benefits include

improved consistency over the tested parameter range, as well as greater improvement in the objective function values. These results demonstrate that the constraint-based technique is able to produce an improvement in consistency for both the active losses and the generator reactive utilisation. It is this improvement that is particularly important in practice, because it means that the desired trade off between the two objectives can be reliably achieved.

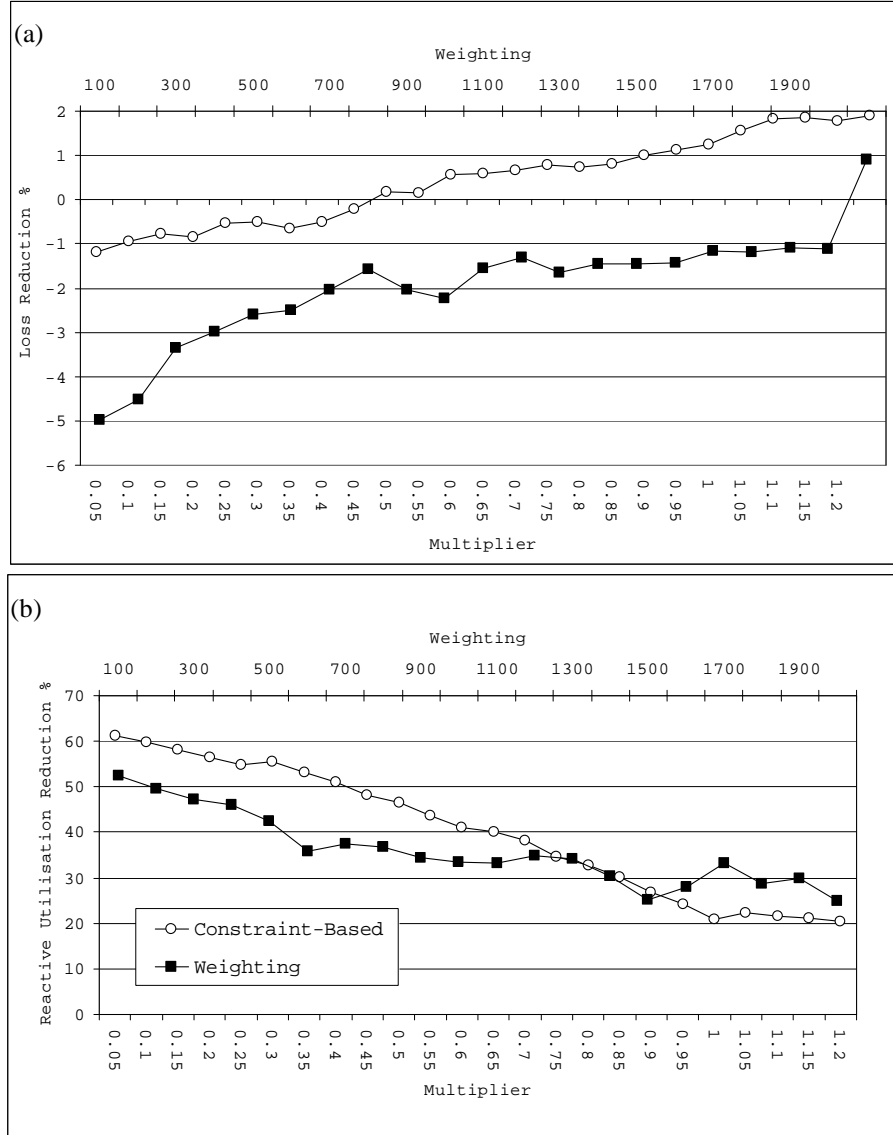


Figure 6-11. (a) Active losses reduction achieved by the weighting technique and constraint-based technique. (b) Reactive utilisation reduction.

6.6.4 Standard deviation of the weighting and constraint-based results

Figure 6-12 shows the standard deviation in the generator reactive utilisation reduction results achieved by both the weighting and constraint-based multi-objective techniques. This figure clearly demonstrates the consistency of the

constraint-based technique and shows that the smallest standard deviation in the generator reactive utilisation is obtained using the constraint-based technique with a multiplier of 0.7.

Figure 6-13 shows the variation in the standard deviation of the transmission losses improvement values over the investigated range of parameter values. The standard deviation values in Figure 6-13 are generally lower than those in Figure 6-12, but the constraint-based technique still manages to achieve a lower standard deviation than the weighting technique over the investigated range. It is interesting to note that the standard deviation in the reactive utilisation weighting technique results with a value of $W_L=0$ had a value of 16.4, which is much greater than the other values shown in Figure 6-13. The averaged standard deviation of the reactive utilisation reductions from the constraint-based and weighting techniques was 10.1% and 27.8% respectively. The losses reduction standard deviation was 1.7% and 3.2% respectively.

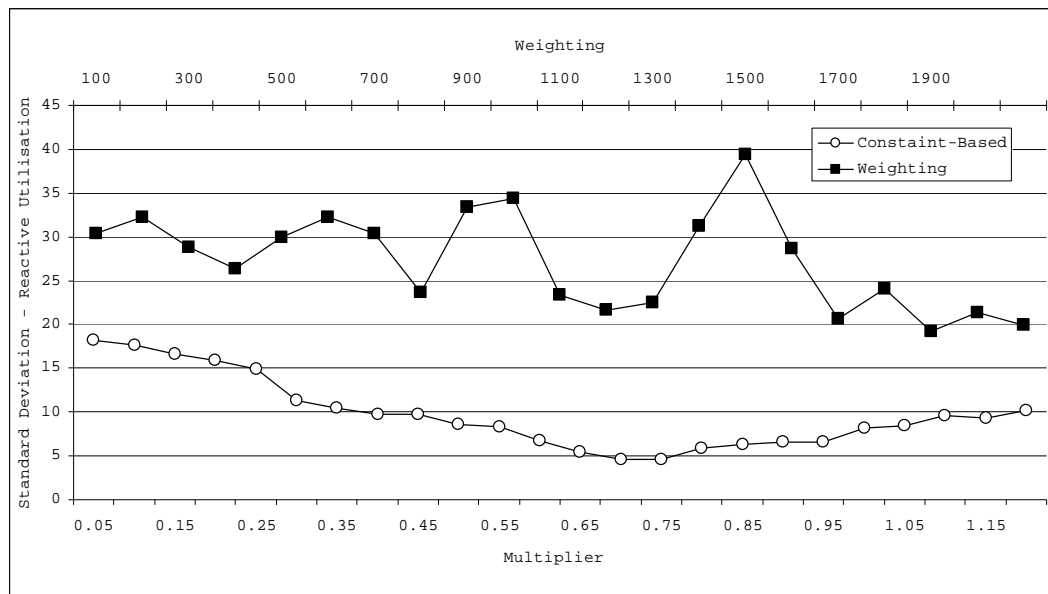


Figure 6-12. Standard deviation of the reactive utilisation reduction results from the weighting and constraint-based techniques.

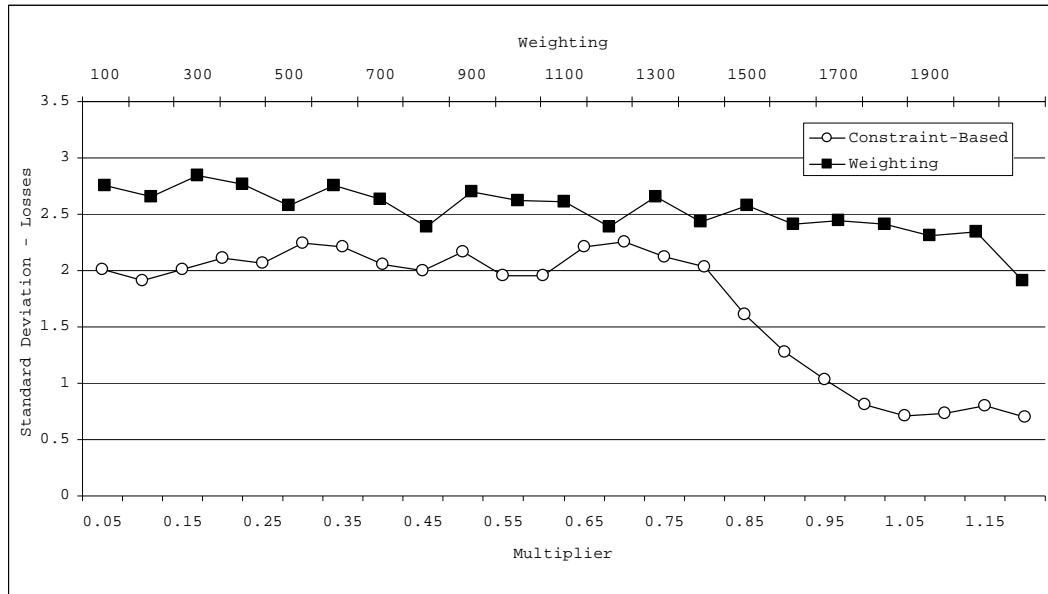


Figure 6-13. Standard deviation of the active losses reduction results from the weighting and constraint-based techniques.

6.6.5 Pareto distribution

In order to identify the phenomena discussed in section 6.2 concerning the identification of an even distribution of points on the Pareto Curve, we now plot the active losses reduction % against the generator reactive utilisation reduction % in Figure 6-14. The weighting technique results show a clustering of points, while the constraint-based technique results show a fairly even distribution of points. The results shown in this figure suggest that the constraint-based technique is better at determining the Pareto Curve on these large networks.

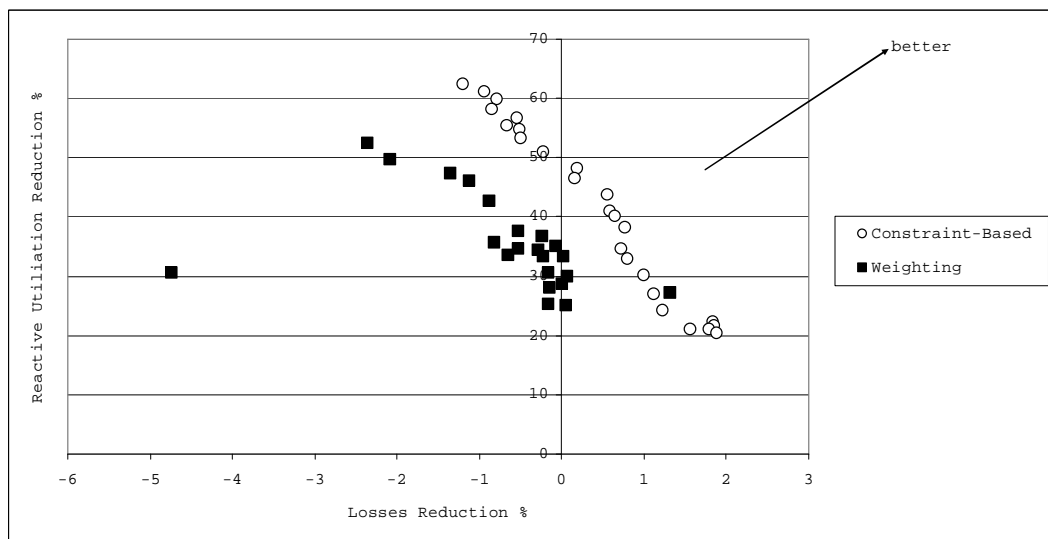


Figure 6-14. Comparison of Pareto points obtained using the weighting and constraint-based techniques on GB networks.

6.6.6 Discussion

The extensive results that have been collected, analysed and presented in this section were obtained using 26 large-scale GB network studies. These results indicate that the constraint-based technique is more robust than the weighting technique for performing multi-objective optimisation. The analysis that has been presented in this section will be important to a practical implementation of a multi-objective SCORPF because it will need to be effective, robust and fast.

Figure 6-11 shows that the constraint-based technique managed to achieve a consistent variation in the generator reactive utilisation objective value, while the weighting technique did not. Figure 6-11 also indicates that there were improvements in the consistency of the losses reduction. These are important considerations that favour the application of the constraint-based multi-objective technique over the weighting technique. Figure 6-14 also demonstrates that the constraint-based technique managed to find smaller objective function values than the weighting technique on the 26 large-scale networks.

6.7 Comparison with Operational Practice

6.7.1 Objective improvement

This section concentrates on the details of the solutions obtained using the constraint-based technique and a comparison is made to the manual solutions obtained by ENCC engineers.

SCORPF was solved using the constraint-based technique with multiplier values ranging from 0.3 to 1.0 on four large-scale network studies that had been prepared by ENCC engineers that were reflective of network conditions on Thursday 22nd May 2008. Each study corresponded to a different cardinal day/night demand point [107]. Table 6-3 shows a numerical breakdown of the results obtained from the initial ENCC network study, the optimised version of this study without extra branch reactive flow constraints and several optimised studies with the extra branch reactive flow constraints. Figure 6-15 presents the results obtained from the ENCC network study, representative of network conditions at 04:00, over a

range of multiplier values. The horizontal lines at the top of the figure indicate the level of active losses and generator reactive utilisation in the initial ENCC study. From the figure it can be seen that losses reduction has been achieved simultaneously with a reduction in generator reactive utilisation for all values of the multiplier. A multiplier value of 1.0 yielded a loss reduction of 1.6% and achieved a generator reactive utilisation reduction of 31%, a multiplier of 0.3 yielded a loss reduction of 0.6% and a generator reactive utilisation reduction of 50%. Figures 6-16, 6-17 and 6-18 present similar results at different study times. These results indicate that the SCORPF, with the constraint-based technique's additional reactive constraints, can improve the ENCC's network study. The optimised solutions have managed to reduce a combination of active losses and generator reactive utilisation.

		Study Time			
		04:00	10:40	16:30	20:30
Initial control room network	Losses	307.27	724.63	724.89	643.06
	Q-Utilisation	4397.28	7524.18	7382.59	7583.46
Loss Reduction no Extra Constraints	Losses	304.19	719.25	712.26	626.64
	Q-Utilisation	4027.21	7819.72	7023.14	7611.37
Loss Reduction Multiplier=1.0	Losses	300.21	712.58	713.48	625.21
	Q-Utilisation	3112.40	5027.70	5106.60	4382.30
Loss Reduction Multiplier=0.5	Losses	305.46	714.86	715.27	625.73
	Q-Utilisation	2795.20	4494.30	4156.50	4249.80

Table 6-3. SCORPF active losses reduction results performed with and without branch reactive flow constraints.

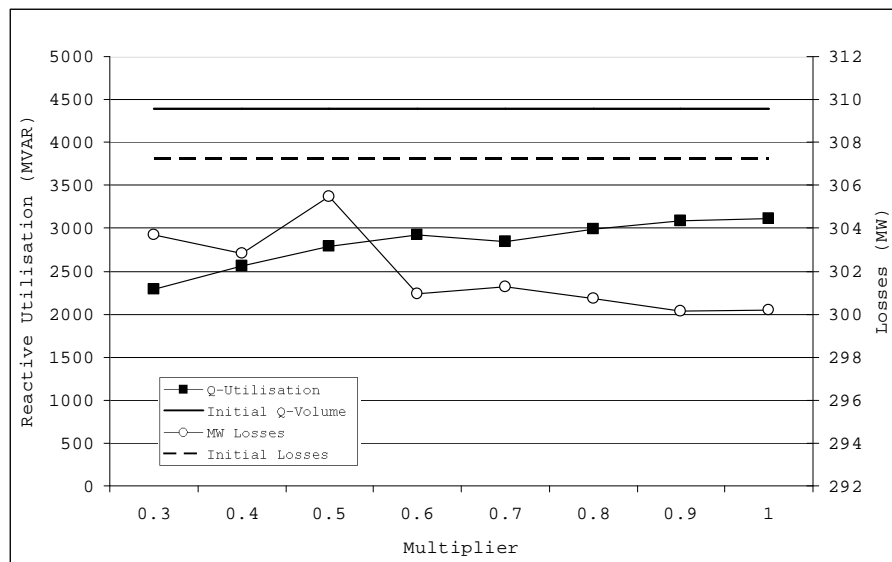


Figure 6-15. SCORPF results for ENCC study 22nd May 2008 04:00.

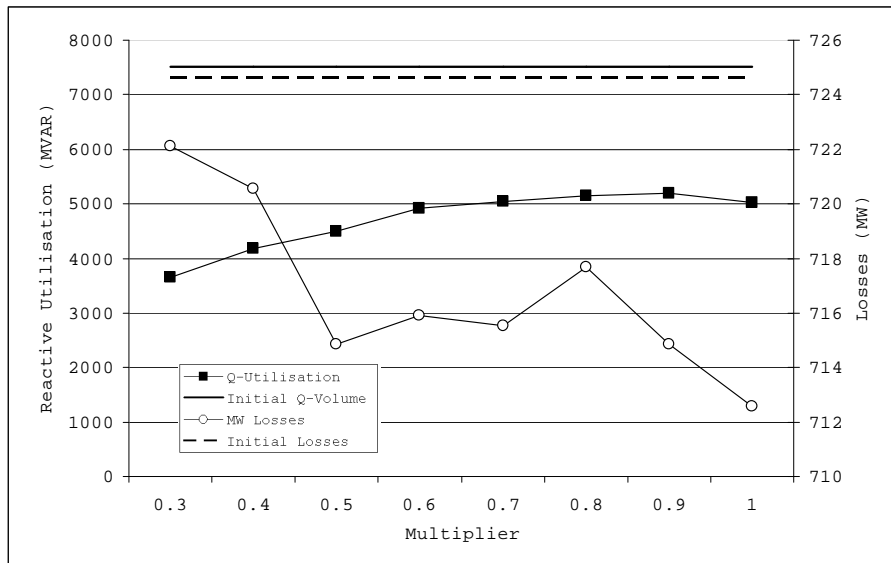


Figure 6-16. SCORPF results for ENCC study 22nd May 2008 10:40.

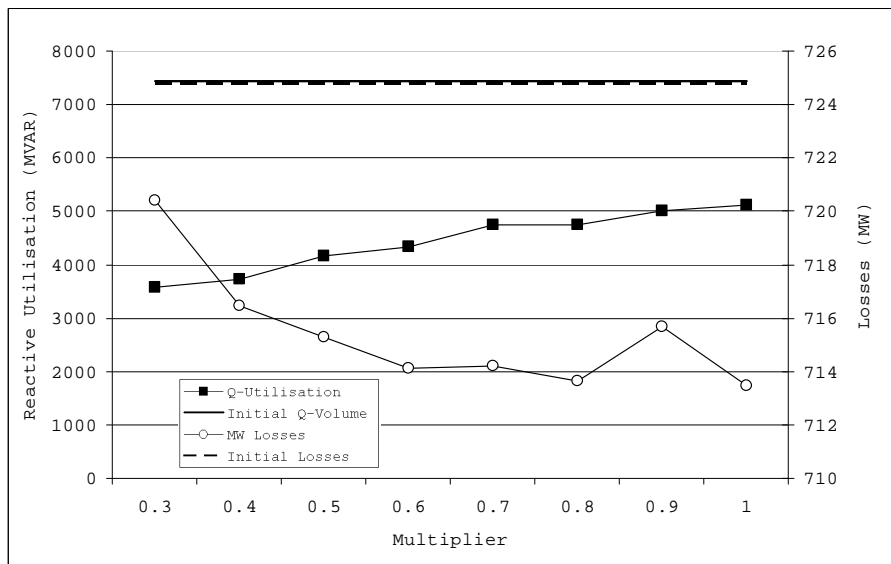


Figure 6-17. SCORPF results for ENCC study 22nd May 2008 16:30.

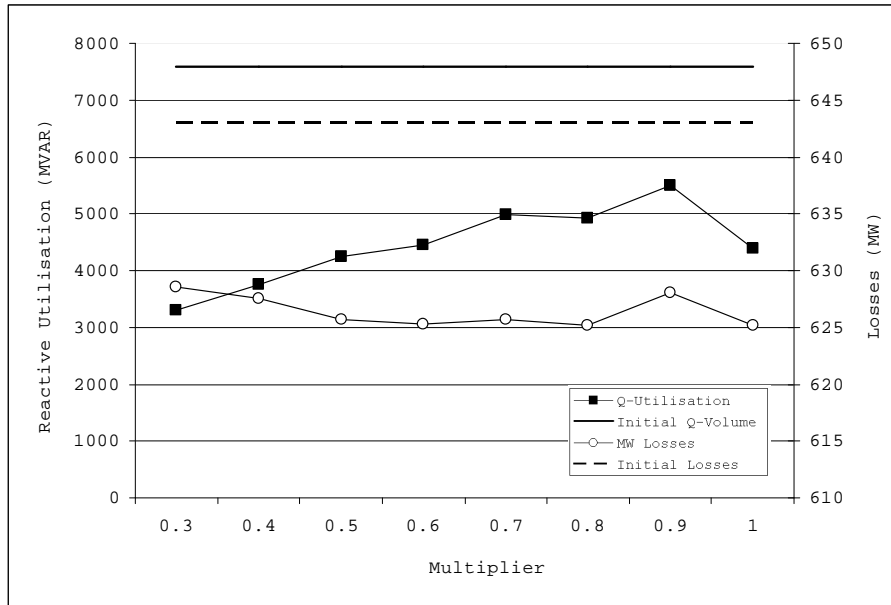


Figure 6-18. SCORPF results for ENCC study 22nd May 2008 20:30.

6.7.2 Voltage margin improvement

The voltage margin of a GB network study prepared by the ENCC and representative of 22nd May 2008 at 16:30 is investigated in this section. A MATLAB program was written to increase the demand incrementally and solve the Newton Raphson power flow repeatedly to determine bus voltages on the network. If the power flow did not converge then the demand was reduced to the last converged value and the increment was reduced, such that the voltage collapse point could be accurately determined. Figure 6-19 shows these voltage margin results, which indicate how the average voltages on the transmission network vary as demand is increased uniformly across the network.

Figure 6-19 shows voltage margin results for the network study prepared by the ENCC, which are labelled ‘initial’ in the figure. The figure also shows results from three optimised networks, which were prepared using the same process as described in section 6.7.1. Constraints with the multiplier’s 0.3, 0.5 and 1.0 were applied; in the figure the voltage stability margin results from these optimised networks are labelled as ‘0.3’, ‘0.5’ and ‘1.0’ respectively.

The results shown in Figure 6-19 suggest that SCORPF can produce networks with greater voltage security. These results increase confidence in the

optimisation process, as they show that the optimised network is further away from the voltage collapse point. The maximum increase in loadability between the initial study and the optimised study was 3.1%. The improved voltage security is achieved because SCORPF has reduced the reactive utilisation of generators, which has had the effect of creating lagging reactive reserve. This improvement in lagging reactive reserve means that the network is able to cope with an increased loading before the power flow becomes non-convergent.

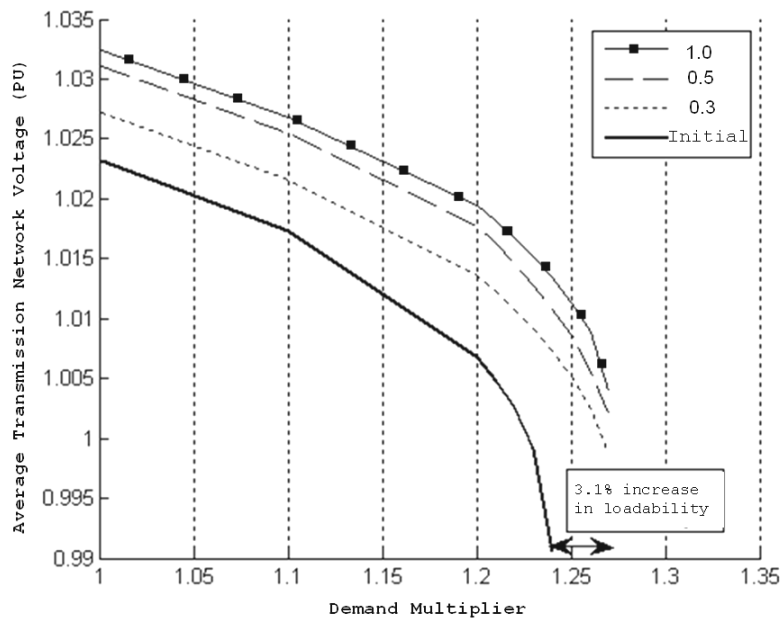


Figure 6-19. Voltage stability margin for ENCC study 22nd May 2008 at 16:30.

6.7.3 Comparison with the live network

The results presented in Figure's 6-15 to 6-18 indicate that optimisation can be used to reduce the generator reactive utilisation in the control centre's offline study by around 50%, as well as reduce active losses and improve the voltage margin. This section extends the above investigation by considering the results from a further nine offline network studies, a comparison with the network conditions at a snapshot of the live network corresponding to the time represented by the offline study is also presented.

The generator reactive utilisation can vary significantly between an offline planning study and the corresponding online snapshot. This difference occurs because the Transmission Dispatch Engineer, whose role is to implement voltage

switching actions, may not follow the voltage targets determined in the study. The reasons for not following the targets arise out of limitations with the offline study. The offline study is designed to represent and be secure for a snapshot in time - it does not therefore take into account the dynamic nature of the network.

To meaningfully determine the generator reactive utilisation savings that can be made it is necessary to compare the optimised offline network study to the corresponding live network snapshot. A snapshot of the live network is recorded approximately every ten minutes by the state estimator. The generator reactive utilisation in each snapshot was compared with the generator reactive utilisation in the offline network study and the optimised version of the offline network study. The last column of Table 6-4 show these comparison results in terms of the percentage improvement achieved by the optimised study compared to the corresponding live network snapshot. The other columns in Table 6-4 show the percentage improvements relative to the original offline network study.

	Transmission losses reduction %	Voltage margin inc %	Q-Utilisation saving relative to plan %	Q-Utilisation saving relative to live network %
12:00 25th May	2.12	2.42	52.94	39.62
16:00 25th May	2.69	3.28	58.77	56.20
21:00 25th May	2.23	3.17	54.57	48.66
12:00 22nd May	1.35	3.20	40.27	28.37
04:30 22nd May	0.59	1.90	36.43	-65.95
16:00 22nd May	1.33	3.10	43.70	15.65
21:00 22nd May	2.69	4.80	43.96	28.74
04:00 26th June	1.94	0.00	53.65	44.94
12:00 26th June	-0.22	5.04	54.64	47.30
16:00 26th June	1.42	2.50	50.10	47.91
21:00 26th June	-0.64	0.82	52.40	51.19
04:00 30th June	1.72	1.26	59.90	35.61
12:00 25th Nov	1.56	-1.70	29.23	17.45
Average saving	1.44	2.29	48.50	30.44

Table 6-4. Improvement in the active losses, voltage margin and reactive utilisation using SCORPF with the constraint-based technique using a multiplier of 0.5.

Table 6-4 shows that SCORPF with the constraint-based technique has managed to achieve an improvement in all metrics. The average active losses reduction achieved by the SCORPF on this selection of networks was 1.4%, which is equivalent to a reduction in emissions of around 50,000 tonnes of CO₂. The average voltage margin improvement was 2.3%, which is a measure of the

improvement in system loadability. This has economic value because it means that the optimised network has less risk of demand loss [108].

Table 6-4 shows that the generator reactive utilisation improvement relative to the live network is less than the generator reactive utilisation improvement relative to the offline network study. This indicates that the real-time network generator reactive utilisation is lower than in the offline network study, which means that the ENCC Transmission Dispatch Engineer is doing better than the manually prepared offline network study. Table 6-4 indicates that a 30% reduction in the networks generator reactive utilisation, relative to the live network, is possible using SCORPF technology with the constraint based technique. This saving would improve system security as generators would be operating closer to zero reactive output enhancing reserve, however this saving in generator reactive utilisation would not translate directly into a reactive cost saving, because the quoted generator reactive utilisation saving is made on the low voltage side of each generator transformer. To ensure a reduction in reactive costs is achieved the optimisation should reduce the commercial boundary reactive flows, which are measured at the high voltage side of each generator transformer. The study presented in Table 6-4 was repeated with the reactive flows optimised and measured at the commercial boundaries. On average the SCORPF achieved an 8% reduction in the reactive flow across commercial boundaries this corresponds to an 8% reduction in reactive costs, since all generators were paid at an identical default price for reactive utilisation in 2009/10. If the full value of this saving could be achieved in practice then it would be equivalent to a saving of around £4 million per annum in generator reactive utilisation costs.

6.8 Summary

This chapter compared a constraint-based technique to a weighting technique for multi-objective SCORPF. Results from a range of IEEE network models and practical large-scale GB network models suggest that the constraint-based technique is able to provide more consistent and predictable results. In control timescales it is not possible to map the entire Pareto Curve to allow the most desirable weighting value or multiplier value to be chosen on a case by case basis. This means that any practical SCORPF process needs to rely on fixed weighting

or multiplier values depending on whether one is using the weighting technique or constraint-based technique. This highlights the requirement of being able to achieve a predictable and repeatable trade off in the reduction of the objective functions for a given value of the multiplier or weighting. Evidence was presented in Figures 6-12 and 6-13 that the constraint-based technique was able to achieve better repeatability. These figures have shown that the standard deviation of the generator reactive utilisation and the losses reduction results from the constraint-based technique are substantially lower. All investigations involving the weighting technique considered the same range of weighting values, but it was noted that for some network cases there was a low sensitivity to changes in the weighting over a portion of the weighting range. This phenomenon can be seen in Figure 6-6a and Figure 6-6b. Conversely the constraint-based technique did not suffer from this insensitivity issue.

The prototype voltage optimisation tool that will be described in the next chapter is based on the constraint-based technique and therefore requires an appropriate multiplier value to be chosen. This multiplier value can be chosen using the results in Figure 6-10. For example to achieve the maximum reduction in generator reactive utilisation, without increasing losses on average, requires a multiplier of 0.3 for daytime networks or 0.9 for night time networks. These values were determined from the averaged results in Figure 6-10 by reading off the multiplier value at the appropriate position where the results line crossed the x-axis. These multiplier values result in an average of a 60% and 22% reduction in generator reactive utilisation respectively with no increase in active losses. On the other hand a multiplier of 0.5 achieves a reduction in generator reactive utilisation with a significant reduction in active losses. These studies demonstrate that SCORPF can achieve an environmentally significant reduction in active losses, a reduction in reactive costs, a reduction in generator reactive utilisation and an improvement in the voltage stability margin.

This chapter has highlighted the requirement of being able to achieve a repeatable trade-off between the active losses and generator reactive utilisation objectives, but has not explained how one should establish the required trade-off. Zhu and Irving [29] describe an analytic hierarchical process (AHP) for determining the

weighting factors of different kinds of objectives by considering the relative importance of these objectives. Further development of the constraint-based technique should therefore consider utilising an AHP based method for determining appropriate multiplier values.

Chapter 7

Development and Evaluation of a Prototype SCORPF Control Centre Tool

7.1 Introduction

In the mid-1990s National Grid, the GB electricity transmission system operator, implemented an operational SCORPF tool called ACCORD. While initial engineering experience using ACCORD has been described as favourable [71], the tool was eventually withdrawn from service due to several practical limitations. ACCORD was limited to just 20 contingency cases, which meant that the final solution was not guaranteed to be secure against all credible contingency events and occasionally suffered from non-convergence [17]. ACCORD was also limited by the fact that it did not consider shunt capacitors and shunt reactors as optimisable control variables, which is a key omission since these controls are a useful source of static reactive compensation. An enhancement to the ACCORD tool has now been developed and implemented in the control centre as a result of this Engineering Doctorate project that has the capability to robustly handle more than 800 contingency cases simultaneously and is able to handle optimisable shunt controls. This prototype tool has given ENCC engineers direct access to a fully automated SCORPF process, allowing them to become engaged and build confidence in reactive power optimisation technology. This chapter will demonstrate that barriers to effective implementation of the prototype SCORPF tool arise due to a mixture of human factors and technical factors. Feedback and development of the prototype SCORPF tool will also be described in this chapter [109].

7.2 EVOT Development

7.2.1 General overview

The Ella Voltage Optimisation Tool (EVOT) is a prototype demonstration tool developed within this project to allow ENCC engineers to utilise SCORPF [72]. The tool is simple to use, and is intended to clearly demonstrate the benefits of utilising security constrained reactive optimisation within a control environment. It is envisioned that the EVOT tool, or a similar tool based on the EVOT process, could be utilised by the ENCC to derive optimised voltage targets. It is proposed that the Transmission Despatch Engineer (TDE) could despatch reactive switching instructions guided by these optimal voltage targets [20]. It is agreed by both management and ENCC engineers that securely optimised voltage targets could allow for a more robust business process.

EVOT has been designed to securely optimise the voltage targets of generators, voltage set-points of SVCs and switching positions of available shunt capacitors and reactors [19,23,22]. The tool optimises the system voltage profile to within the constraints that ENCC engineers normally work within. These constraints are generally stricter than those specified in the SQSS [3]. The optimisation solves the multi-objective optimisation problem by minimising active transmission losses, while applying the additional reactive branch flow constraints that were introduced in chapter 6. The constraint-based technique was chosen over the conventional weighting technique due to the improved robustness and the superior solutions that it can generate - see section 6.6.3 [20].

7.2.2 EVOT usage

EVOT is intended to be evaluated by the Transmission Analysis Engineer (TAE), whose role includes the setting up of a voltage profile in offline studies during control timescales. To run EVOT the ENCC engineer first needs to prepare an offline study by following the standard business procedure utilising National Grid's in-house power analysis suite called ELLA [72]. This preparation process, which was described in section 3.3.6, involves updating an earlier study with a future demand and generation profile. The ENCC engineer applies a system wide

voltage profile setting and manually adjusts the profile to achieve a secure study. The ENCC engineer then selects credible single and double circuit outages and saves the study and the associated contingency data. EVOT tool run time options can then be modified by the user if required. Finally the ENCC engineer executes the EVOT tool, which automatically picks up the correct files and creates a new optimised offline study within a few minutes.

The EVOT tool user options modify the optimisation process. For instance the user can set the constraint multiplier value on the reactive branch flow limits in order to favour either the active losses reduction objective or the reactive utilisation reduction objective. The user can also choose between reducing the reactive utilisation on the LV side of each generator transformer and reducing the reactive flow across the metered commercial boundaries, which are on the HV side of generator transformers. Version 1 of the EVOT tool defaults to minimising the reactive flows across commercial boundaries, which should lead to solutions that have a lower cost.

The EVOT tool runs in two parts. The first part of the tool runs on an HP275 server and performs an initial conversion of the data from National Grid's in-house native power flow format (ELLA) to SCOPE format. SCOPE version 12.2 is a commercial SCORPF package that was applied within this research to solve the GB transmission network optimisation problem [39]. A Windows server, which receives data from the HP275 server by FTP, runs the second part of the EVOT tool. The Windows server executes further conversion processes and the SCOPE optimisation process, while sending update messages back to the HP275 server informing the user of the progress. When the Windows part of the optimisation finishes the optimised study is sent back to the HP275 server by FTP. The HP275 server then picks up the optimised study and moves it to the appropriate user directory. The engineer can then review the voltage profile of the optimised study using the ELLA graphical environment and judge the quality of the optimised study against the original.

This two part process was utilised for the following reasons:

- Running the prototype tool separately from the production HP275 server was more secure and less likely to interfere with other operational processes.
- Running the tool in Windows allowed MATLAB to be used to code the conversion and optimisation execution functions.
- The SCORPF solved significantly more quickly on a standalone Windows machine compared to the same SCORPF running on a shared HP275 server. The Windows machine was a 3GHz Pentium 4 with 2.5GB of memory.

7.2.3 High-level process overview

The main aim of EVOT is to allow ENCC engineers to build confidence in SCORPF techniques. EVOT has been designed to accurately model the National Grid transmission network, the process for obtaining an accurate network model was discussed in section 4.4. EVOT has also been adjusted so that it robustly converges for a range of different network conditions and starting points. Figure 7-1 shows the flow of the EVOT process from the initial sub-optimal study, to the EVOT execution and finally to the review stage.

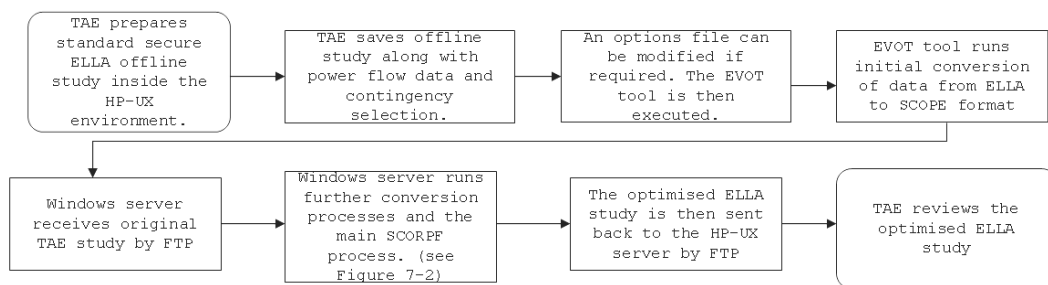


Figure 7-1. High level EVOT process.

As indicated in Figure 7-1 the main optimisation process is carried out on the Windows server, which automatically detects the incoming optimisation job. An FTP application is continuously active with a fixed IP address, so that the HP275 part of the EVOT tool can connect at any time. A monitoring tool running on the Windows sever detects incoming optimisation jobs and automatically runs the main MATLAB process. The main MATLAB process includes conversion and optimisation formulation routines, the main SCOPE optimisation and post

processing routines. When the EVOT prototype tool completes the optimisation process, a short report is presented to the ENCC engineer showing the percentage reduction in reactive utilisation and percentage reduction in active losses relative to the original study. The ENCC engineer can then check the security of the optimised solution directly in the familiar ELLA environment.

Section 7.2.4 will describe the details of the processes running on the Windows server and section 7.2.5 describes the SCORPF execution process.

7.2.4 Windows server processes

Every time EVOT is invoked by the user a script running on an HP275 server attempts to communicate with the Windows server to send it the offline study for optimisation. The script then waits for the optimised network to be sent back. The process running on the Windows server is shown in Figure 7-2. The process proceeds by adding extra optimisation data to the incoming study such as voltage constraint limits and available optimisable control settings. Constraints on transformer reactive flows are set-up using the technique described in section 6.3. The main SCORPF stage is then performed, which is described in the next section. Finally the original study is updated with the optimised voltage control settings to create the new optimised study. If the optimisation causes losses to increase by more than 3% using an objective function that is weighted heavily towards reactive utilisation reduction, then the optimisation is repeated with parameters that are more favourable towards transmission losses reduction.

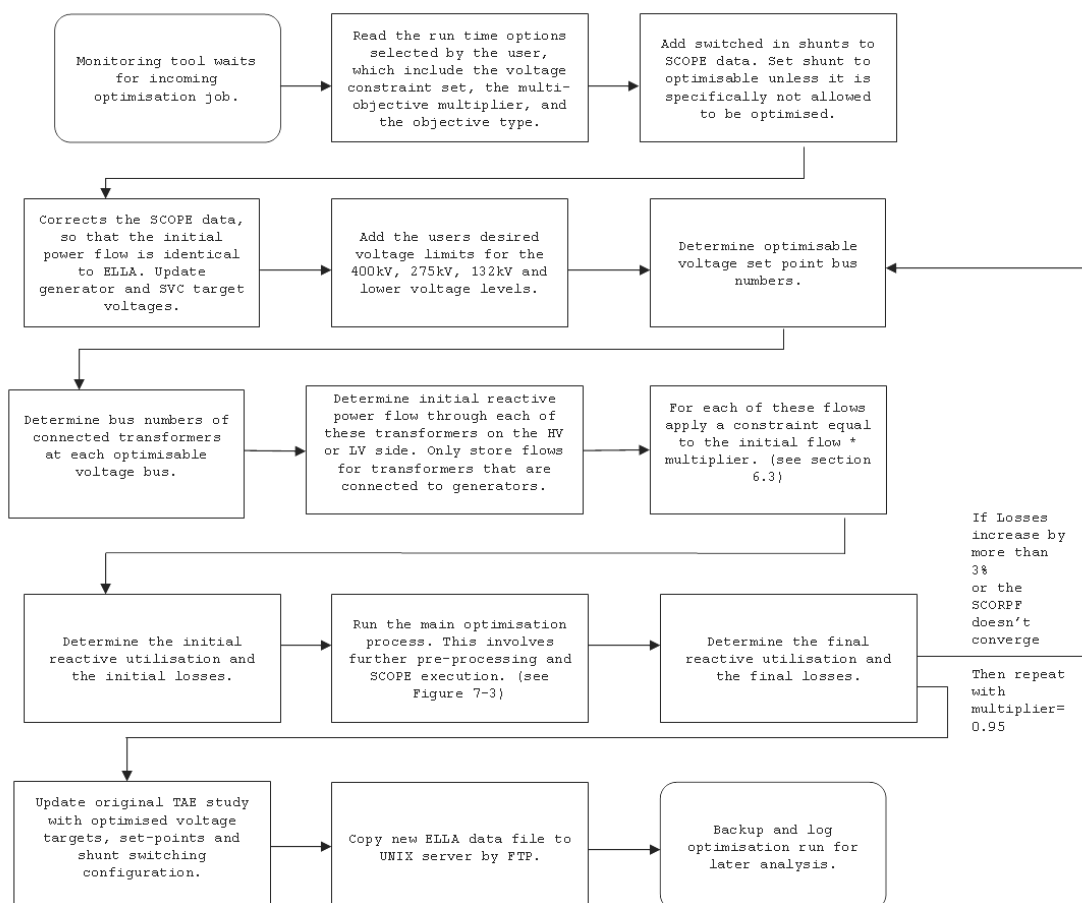


Figure 7-2. The EVOT process running on the Windows server.

7.2.5 Three staged SCORPF process

Figure 7-3 below shows the SCORPF execution process. Contingency cases that are not feasible in the initial secure solution are removed, as these are likely to be non-credible cases. Note that the ENCC engineer will run a full contingency analysis after the optimisation process completes in order to ensure that the network is still secure. A three staged optimisation process is then performed. The three stage optimisation proceeds by executing an initial network optimisation, this is followed by an SCORPF assuming all controls are continuous, discrete controls are then rounded off and finally SCORPF is performed with only continuous controls [19]. At each of these stages the SCORPF problem, which was formulated by the proceeding steps, is solved by SCOPE. SCOPE solves the LP problem using a compact formulation in terms of the control variables, the approach was developed by Stott et al. [33, 34, 40] see section 2.2.

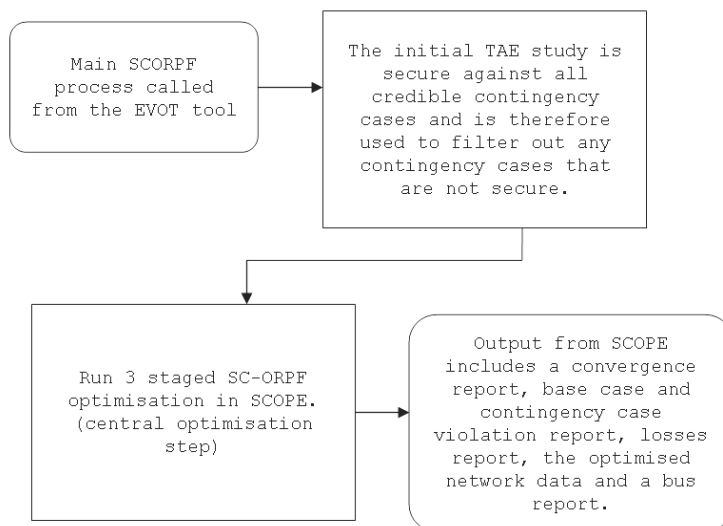


Figure 7-3. Main optimisation process called by the EVOT tool.

7.3 EVOT Feedback

7.3.1 Gathering feedback

To gather the required feedback from ENCC engineers required a number of steps. The first step involved engaging both ENCC engineers and managers. Presentations were made to a number of different groups with the company highlighting the advantages of using EVOT, likely benefits and results from the tool. These presentations were successful in initially achieving engagement. The second step involved identifying important contacts that had the necessary interest and appropriate experience to be able to provide constructive feedback. Regular meetings were held with these contacts in order to establish a firm working relationship. The third step involved teaching ENCC engineers to use the EVOT tool and working with them to resolve any issues they had using the prototype tool. In addition a user guide was written to help these engineers use the EVOT prototype tool more effectively [110]. Finally a schedule for receiving the feedback was agreed.

The EVOT prototype tool was designed to log and backup every optimisation study that was sent to it. This provides information regarding when the tool is being used and whether it is necessary to repeat the optimization. This feature was particularly important for finding and removing bugs in the EVOT tool.

7.3.2 Summary of feedback

This section lists the feedback that was obtained from ENCC engineers in relation to EVOT version 1. While the optimised studies confirmed some existing operational practices, it also suggested some new ideas. The following strengths were highlighted:

- 1) A full contingency analysis was performed on the optimised solution using ELLA. This analysis confirmed that the optimised study was secure against the 800 credible contingency events and met all SQSS standards. For comparison it is interesting to note that the ACCORD tool was only guaranteed to be secure against 20 contingencies.
- 2) EVOT took less than four minutes to find a solution and was easy to use. This represents a marked improvement over the ACCORD tool, which could sometimes run to the maximum number of allowed iterations taking around 20 minutes [71]. Operators of the ACCORD tool were required to abort the optimisation process by watching the convergence log output [71]. In comparison the EVOT tool was found to be more reliable in this respect
- 3) The optimisation achieved a lower cost solution than the manually prepared solution.

The feedback also highlighted the following weaknesses:

- 4) Several locations on the 275kV and 400kV network had voltages that dropped to less than 1pu in mid-day studies. This was within the SQSS standard, but was outside the operational limits applied by ENCC engineers.
- 5) Several locations had voltages that were higher than the operational limits. This was a particular issue on the 275kV network. The exact upper limit, which ENCC engineers considered acceptable, was location specific. Some 400kV sites were exactly on the upper limit of 416kV, which was considered to be too high by some ENCC engineers.
- 6) Shunt capacitors and reactors that were available for optimisation, but switched out, were not being included in the optimisation. This occurs

because the ELLA data model that was being used only stores the shunts that are actually switched in. All available shunts should be optimisable.

- 7) The solution from SCORPF should not have contradictory shunt switching configurations. For example three 60 MVar capacitors and one 180 MVar reactor being switched in at the same site would be unacceptable.
- 8) The reactive output from SVCs should not increase during the optimisation. Ideally most SVCs should be operated with an output of around zero MVAr for the intact network condition. There was concern that the optimisation was achieving the reduction in generator reactive utilisation by increasing the reactive output from SVCs. Although this is economically correct, it is not consistent with current operational practice.
- 9) Ideally generators should not produce or absorb more than 100 MVAr.
- 10) Ideally the SCORPF process should minimise the number of generators that are absorbing MVAr.
- 11) Total generator lagging reactive reserves should not be eroded by the optimisation.
- 12) Generators should not be pushed to their respective reactive control limits.
- 13) ELLA produces a report showing generator reactive output on the LV side and does not directly present reactive flow across commercially metered boundaries. This means that any demonstration of SCORPF needs to optimise the LV side flows, so that improvements can be readily observed by ENCC engineers using ELLA.
- 14) The ELLA version of the SCORPF solution sometimes took more power flow iterations to converge than the original unoptimised solution. This problem seemed to arise due to a difference between the SCOPE and ELLA power flow solvers, and the optimised solution occasionally having transformer taps closer to their limit.
- 15) The ELLA study is a snapshot, using predicted demand and generation, with continuous tap ranges and doesn't model the generator reactive capability curve. EVOT also suffers from these same drawbacks.

- 16) The EVOT prototype tool is still limited to a maximum of 1000 contingencies.

Lastly the feedback highlighted the following new ideas:

- 17) The optimised studies gave experienced ENCC engineers' an alternative way in which to securely dispatch the GB transmission system voltage.
- 18) The optimised studies indicated the importance of adjusting the voltage profile of the GB transmission system to make effective use of the network gain from individual circuits.
- 19) In some areas a large difference in voltage was observed between adjacent nodes. For example in the optimised peak time study, Pentir is operated at 415kV and nearby Deeside is operated at 407kV.
- 20) The optimised peak time study managed to achieve a high voltage in the South West Peninsula region e.g. Indian Queens had a voltage of 413kV
- 21) Not all areas were pushed towards their maximum limit. Some areas were moved towards their lower limit e.g. Drakelow had a voltage of 399kV.
- 22) The optimised voltages around London were found to be particularly high
- this is consistent with current practice for a peak time study.

7.4 EVOT Version 2 Development

7.4.1 Response to feedback

EVOT version 2 was designed to address many of the concerns highlighted in section 7.3.2. ENCC engineers had confirmed that the tool was able to securely produce an improvement in the objective function, however issues with the optimised solution existed limiting its practical applicability. Much of the feedback listed in section 7.3.2 relate to human operator preferences, as opposed to specific technical or legal issues. ENCC operators will tend to have some variation in the concerns that they raise. It is however essential to address these concerns in order to build confidence in the SCORPF process.

The main improvement in EVOT version 2 was the inclusion of available, but switched out shunt reactors and capacitors in the optimisation. A method is described in section 7.4.2 to do this, which takes into account equipment outages. Another improvement in EVOT version 2 is that it detects and corrects sites that have contradictory shunt switching configurations, the novel processing logic developed to do this is presented in section 7.4.3. The improvements that have been made to the shunt modelling process address the weaknesses identified in section 7.3.2 feedback points 6 and 7.

EVOT version 2 also included the following features to address some of the weaknesses highlighted in section 7.3.2:

- It now minimises the generator reactive utilisation on the LV side of each generator transformer, which corresponds to favouring a generator reactive output of zero. This allows the ENCC engineers to analyse the solution in the environment that they are familiar with. This addresses feedback point 13.
- A soft 93MVar flow upper limit constraint is now applied to all LV generator transformer flows to encourage the solution to appear more reasonable. This change simply ensures that the solution is more appealing to ENCC engineers. This addresses feedback point 9.
- A hard 3MVar reserve limit is now applied to all generators to ensure that the optimisation process doesn't cause reactive limits to become binding. While the normal effect of the SCORPF is to increase reactive reserves, this helps to guarantee that the solution is not operating on a limit. This addresses feedback point 12.
- A soft reserve constraint is now applied to the reactive output of SVCs, so that the output does not increase after the optimisation. It is preferable to operate SVCs closer to zero output in order to minimise the active power consumption of the SVC and to minimise noise pollution. This addresses feedback point 8.
- The 400kV network now has an upper limit of 414kV and a lower limit of 400kV. This addresses feedback point 5.

- The 275kV network now has an upper limit of 287.4kV and a lower limit of 275kV. This addresses feedback points 4 and 5.

7.4.2 Technique for determining optimisable shunts

EVOT version 1 only included switched in shunts during the optimisation. EVOT version 2 now includes switched out shunts that are available to be switched in. This is achieved by adding the following stages to the EVOT process:

- 1) A full list of shunts defined in the ELLA base line data is copied from the HP275 server.
- 2) From this data an ‘optimisable shunt list’ is identified consisting of the shunt names, their location and their corresponding connected busbar.
- 3) Shunts that are dummy or represent network gain are excluded from the ‘optimisable shunt list’.
- 4) The daily outage report corresponding to the study being optimised is obtained. From this report a list of shunts that are on outaged can be identified. These shunts are removed from the ‘optimisable shunt list’.
- 5) Outaged shunts are excluded from the ‘optimisable shunt list’
- 6) The SCOPE data is populated with the available shunts.
- 7) Any errors in the shunt modelling are detected and corrected for. This does not usually lead to any changes in the model, but is here to ensure that the power flow solution in SCOPE is the same solution as in ELLA.

Consultation with ENCC engineers confirmed that the EVOT version 2 shunt selection process was able to the correctly select the optimisable shunt capacitors and reactors.

7.4.3 Corrective technique for contradictory shunt switching

Feedback from EVOT version 1 revealed that the optimisation process was producing, with the given offline input model, a solution that had a contradictory shunt switching configuration such that shunt capacitors and shunt reactors were switched in simultaneously at the same site. Figure 7-4 shows a modification to the central optimisation step of Figure 7-3, indicating when the novel shunt post-processing logic should be applied during the 3 stages of the optimisation. Figure

7-5 shows the shunt post-processing logic that was applied to identify problem sites and store the necessary information required by the corrective central step. If a site possessed a contradictory shunt switching configuration then it was flagged as a problem, available controls were stored and sorted at these sites ready for the corrective step. The corrective central step, which is shown in Figure 7-6, tried to achieve the required susceptance value by switching in shunt capacitors or shunt reactors starting with the biggest available shunt.

The following example illustrates the shunt post-processing logic. In the example Bolney and St John's Wood have been identified as 'problem sites' since they exhibited a contradictory shunt switching configuration. This example illustrates that the shunt post-processing logic is able to determine reasonable solutions. At Bolney the following shunt switching solution was determined by the optimisation:

BOLN11	Capacitor	60 MVar	
BOLN11	Capacitor	60 MVar	
BOLN12	Capacitor	60 MVar	
BOLN12	Reactor	0 MVar	(0 MVar means switched out)
BOLN13	Capacitor	0 MVar	
BOLN13	Reactor	-55 MVar	
BOLN41	Capacitor	0 MVar	

Total switched in: 125 MVar

The solution found by the shunt post processing logic was to switch in only a single BOLN11 capacitor and a single BOLN12 capacitor thereby achieving a total switched in susceptance value of 120MVar.

At St John's Wood the following shunt switching solution was determined by the optimisation:

SJOW12	Capacitor	60 MVar
SJOW12	Capacitor	60 MVar
SJOW12	Capacitor	60 MVar
SJOW41	Reactor	-200 MVar

Total switched in: -20 MVar

The solution found by the shunt post processing logic was to switch out all shunt capacitors and reactors thereby achieving a total switched in susceptance value of 0 MVar.

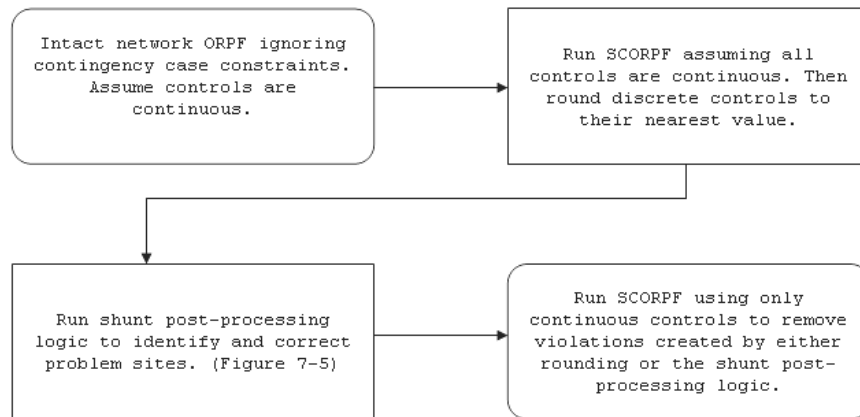


Figure 7-4. EVOT version 2 optimisation process.

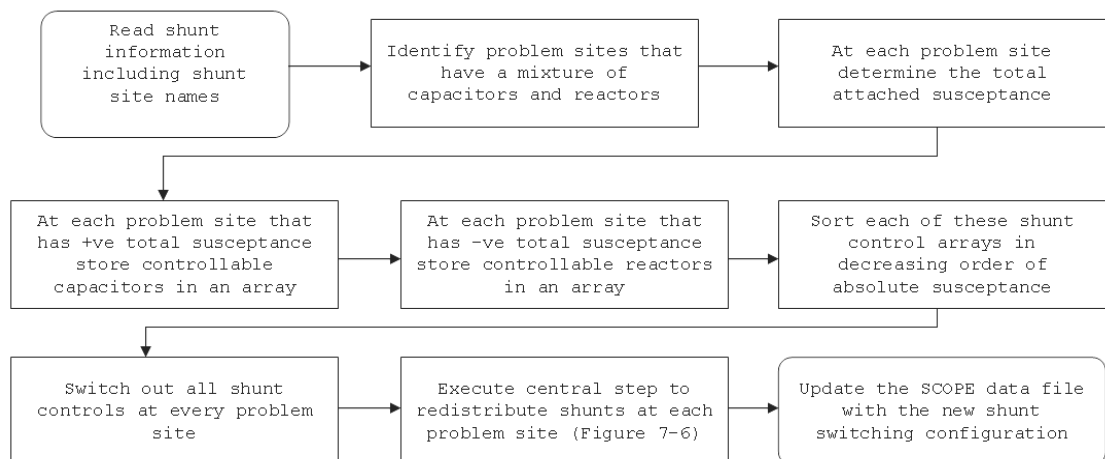


Figure 7-5. Post-processing logic to identify sites with contradictory switching and then correct the problem.

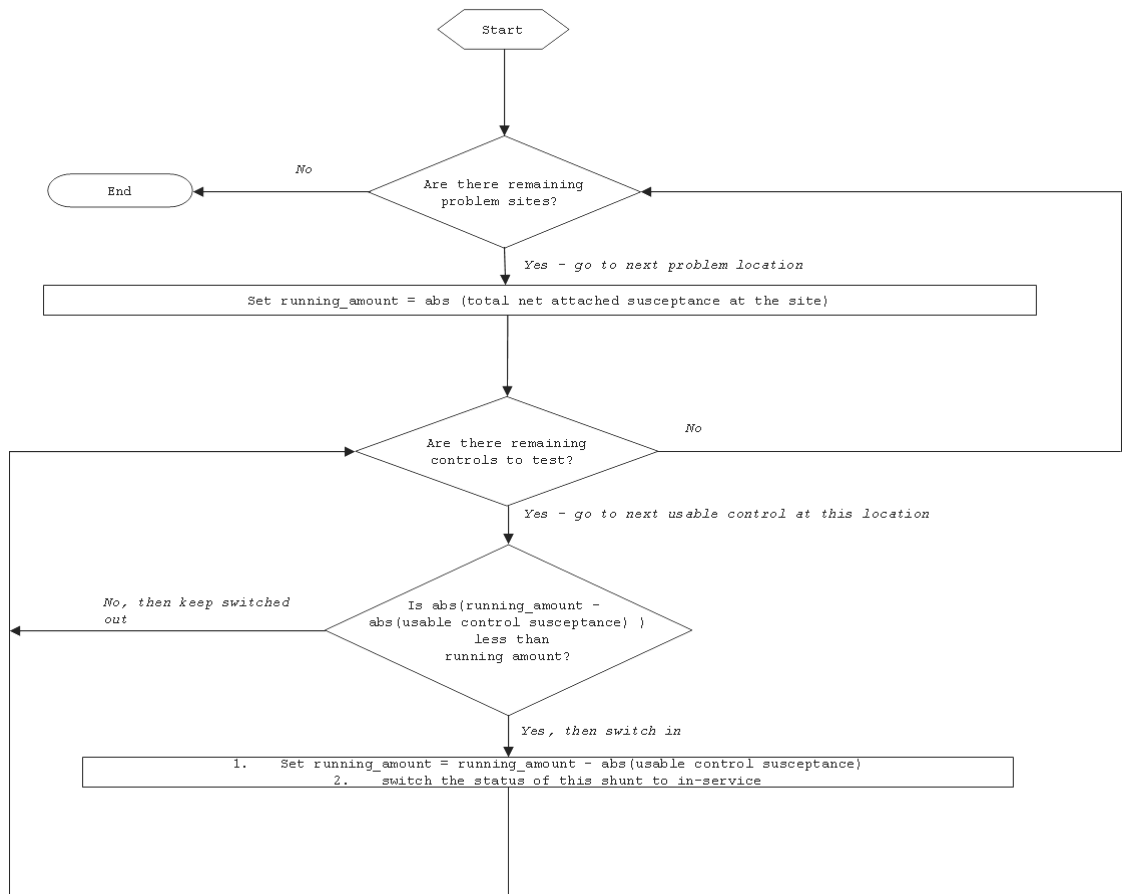


Figure 7-6. Corrective central step to redistribute shunts at problem sites.

7.5 EVOT Version 2 Feedback

7.5.1 ELLA case study – Wednesday 14th April 2010

The feedback from ENCC engineers regarding EVOT version 2 was favourable. The TAE's were generally impressed with the optimised solutions, as the generator reactive utilisation had been substantially reduced by the optimisation process. To illustrate this consider an offline study representative of the network on Wednesday 14th April 2010 at 9PM. Table 7-1 shows a breakdown of the ELLA power flow results from this manually prepared offline study. The areas relate to different parts of the transmission network from Scotland in area one to the South West Peninsula in area eight. ELLA power flow results from the optimised version of this study are shown in Table 7-2. The optimisation process had multiple objectives to minimise active losses and generator reactive utilisation, favouring the later. The optimisation process reduced the reactive utilisation of generators in most areas of the network, with the exception of Scotland. The optimisation made effective use of shunt capacitors and reactors,

which is evident from the large increase in system gain from shunts. The optimisation also managed to increase the system gain from branches. The optimisation increased valuable lagging reactive reserves at the expense of reducing leading reactive reserves. Finally the optimisation achieved the above simultaneously with a reduction in active power losses.

Area	Series Losses		System Gain		Load		Generation		Spare Reactive	
	MW	MVAR	Branch	Shunt	MW	MVAR	MW	MVAR	Lead	Lag
1	61	1294	2542	-730	3627	510	4578	24	1394	2663
2	88	2112	2152	-429	5404	1433	5984	1247	3554	3052
3	101	2996	2206	67	5536	1367	11417	2173	6031	4751
5	130	2704	1783	698	6397	1554	5555	1541	3291	2421
6	131	2965	3528	452	7923	2373	5265	1620	3529	1930
7	73	1460	2910	-1398	4474	1029	2699	762	2235	1876
8	101	2292	3680	242	7968	2231	6630	946	2843	2573
Total:	685	15823	18800	-1098	41329	10497	42127	8313	22877	19266

Table 7-1. Shows results from the original manually prepared offline study

Area	Series Losses		System Gain		Load		Generation		Spare Reactive	
	MW	MVAR	Branch	Shunt	MW	MVAR	MW	MVAR	Lead	Lag
1	61	1273	2559	-585	3627	510	4577	-199	1171	2886
2	85	1995	2185	589	5404	1433	5981	600	2907	3699
3	99	2893	2247	571	5536	1367	11413	1285	5143	5639
5	127	2631	1784	406	6397	1554	5553	1151	2901	2811
6	128	2878	3618	1064	7923	2373	5263	1254	3163	2296
7	70	1400	3005	-1056	4474	1029	2696	402	1875	2236
8	100	2273	3695	346	7968	2231	6628	554	2451	2965
Total:	670	15343	19094	1334	41329	10497	42110	5047	19611	22532

Table 7-2. Shows results from the optimised study

7.5.2 ELLA case study – Saturday 23rd January 2010

The transmission network offline study representative of Saturday 23rd January 2010 at 18:00 was optimised using the EVOT tool. The optimisation process, which focussed on minimising generator reactive utilisation, managed to securely achieve a substantial reduction in the utilisation. However, upon inspection by an ENCC engineer, it was felt that with manual intervention the reactive utilisation in the optimised solution could be further reduced. For example an ENCC engineer demonstrated that the reactive absorption of a single generator could be reduced by increasing its voltage target. Further analysis of the optimised solution, after making this manual modification, revealed that there was an unintended detrimental effect on the total reactive utilisation. Table 7-3 shows the active losses and generator reactive utilisation values determined from the original study, the original study where additional time was spent improving it, the optimised study derived using EVOT and the optimised study with manual intervention. EVOT managed to achieve a substantial reduction in generator reactive utilisation compared to the best manually prepared study. It is interesting and important to

note that the optimised study with manual intervention has a greater reactive utilisation than the optimised study with no manual intervention. This seems to indicate that manual intervention to reduce reactive utilisation after the optimisation can degrade the solution. This result also created greater confidence in the EVOT optimisation process amongst ENCC engineers.

	Original study	Original study additional time	Optimised study	Optimised study with manual intervention
Losses (MW)	1096.2	1085.5	1087.8	1084.4
Reactive Utilisation (MVAR)	6681.6	5047.3	4267.8	4304.6

Table 7-3. Indicates results from various manually adjusted and optimised studies.

7.5.3 Specific areas requiring improvement

The following EVOT version 2 feedback was obtained from ENCC engineers highlighting more weaknesses:

- 1) The 132kV transmission network in Scotland needed stricter voltage limits. The suggested limit range was 132kV to 136kV.
- 2) Some voltages at 275kV busbars were flagged by ELLA as being too high. It is possible to apply a very soft upper limit of 286kV. This would encourage the optimisation process to find a solution that appears more desirable to ENCC engineers.
- 3) On the optimised Scottish 132kV network there were some generators absorbing a significant quantity of reactive power. However ENCC engineers had differing opinions on whether or not Scottish controls should be excluded from the optimisation.
- 4) Several shunts were identified by ENCC engineers as being non-optimisable. This situation can occur when other circuits need to be switched in order to change the switching status of a shunt. It was suggested that the final tool should include a user interface allowing the ENCC engineer to select those shunts that were not optimisable.
- 5) Active power constraint limit violations occasionally got flagged by ELLA. These limit violations were not present in the original solution. This would suggest that the optimisation should also consider active power constraint limits in addition to reactive power constraint limits.
- 6) ENCC engineers stated that manual modification of the optimised solution was sometimes necessary in order to obtain a better solution. However

manual intervention after the optimisation can sometimes degrade the solution, as seen in section 7.5.2.

7.5.4 General feedback on SCORPF for control centre use

This section describes more general feedback from ENCC engineers relating to their requirements from an SCORPF tool such as EVOT. Control engineers need an optimisation tool that not only includes contingency case constraints, but also includes time linked constraints. A time linked requirement exists because an optimisation at a point in time A that is secure at time A also needs to be secure at future time points B, C, and D. This requirement exists because the transmission network voltage dispatch process needs to take into account the time varying nature of power system constraints. It is also important to note that a solution that minimises generator reactive utilisation at point A may cause an increase in generator reactive utilisation at point B. The EVOT tool currently optimises a snapshot of the transmission network and should therefore be adapted to consider the full dynamic transmission network optimisation problem.

ENCC engineers need a tool that is not only capable of generating contingency secure time linked optimal network plans, but is also capable of instructing the Transmission Dispatch Engineer (TDE) how and when to implement the optimal network plan in real-time. Since the EVOT tool was designed to be an offline operational network planning tool, the output of this tool would need to be interfaced with another tool that monitors the network in real-time. This tool would then need to decide how and when to implement the optimised network plan generated by EVOT.

The research carried out by this project has also resulted in the development of a proof of principle real-time optimisation tool that is based on the EVOT process and will be summarised in the following section. This tool uses state estimator snapshots, which are representative of the point in time at which they were taken, to generate a snapshot SCORPF problem. However this real-time SCORPF tool would need further development before it could be used by the TDE as a voltage dispatch advice tool.

ENCC engineers have highlighted the importance of using accurate metering for SCORPF. The TDE currently uses raw metered values to make voltage despatch decisions, however it is recognised that state estimated values are more accurate. It is therefore proposed that SCORPF should use the state estimated values rather than the raw metered values. Confidence in the optimisation results would be increased as a result of this.

ENCC engineers commented that the SCORPF tool should be able to interface with many of the existing control room systems, so that it can accurately determine the status of the transmission network. ENCC engineers have also highlighted the need to model discrete transformer tap changes. Tapping a generator transformer on the National Grid transmission network typically results in a reactive output change of 30MVar. The power flow and optimisation processes currently model transformer taps as continuous variables. A future SCORPF tool would need to use a discrete transformer tap model, so that the solution could be physically implemented on the network.

Finally ENCC engineers have stated that an SCORPF tool that could reduce generator reactive utilisation in offline studies would be useful. The EVOT version 2 prototype tool demonstrates that this is possible with existing SCORPF technology. However, ENCC engineers have clearly demonstrated the need for a more sophisticated voltage despatch advice tool, which takes into account all of the above observations. It is envisaged that the processes that have been developed and utilised by the EVOT prototype tool would form an important component of such an advice tool.

7.6 Real-time SCORPF tool

7.6.1 Model development

Lee [71] stated that the long term aim of the research that resulted in the development of ACCORD was to implement a real-time tool that could run in real-time as a contingency constrained voltage scheduler. This section describes

the development of such a tool that could be used by the ENCC to obtain real-time optimisation advice. A real-time state estimator snapshot of the GB transmission system is produced every ten minutes by the ENCC. This snapshot is stored on an FTP server in an extended IEEE format and consists of an IEEE standard file with extra comment lines describing network state information and control information.

The following steps were developed to create a SCOPE optimisation data file from the state estimator snapshot:

- 1) Remove comment lines from the IEEE extended format state estimator snapshot file. This step also corrects data modelling issues such as isolated nodes and circuits connecting back on themselves.
- 2) Convert file from IEEE to SCOPE version 12.2 data.
- 3) Improve the consistency of the power flow by making appropriate modifications to the SCOPE data model.
- 4) Identify generator HV buses that should be flagged as optimisable voltage control targets. Select 50 HV buses based on the amount of reactive support from generators that is attached.
- 5) Update the SCOPE data file with correct SVC models.
- 6) Add optimisation control data for generator voltage controls, SVC controls and shunt controls.
- 7) Add optimisation constraint data including voltage limits and branch flow limits.
- 8) Flag the transmission network branches to monitor active losses.
- 9) Set up the system slack bus.
- 10) Ensure transformer voltage controls are not conflicting with bus voltage limits.

After following the above steps the resulting SCOPE network data file was detailed enough to perform an accurate power flow and intact network ORPF. The following steps were developed to correctly model contingency cases:

- 1) Read in the list of contingency cases and their associated outages.
- 2) For each of these contingency cases determine the specific branch outages.
- 3) Match up each branch outage with the corresponding branch number in the SCOPE network data.
- 4) If an outaged branch exists in the SCOPE network data then keep it in the contingency case list, otherwise exclude it from the list.
- 5) Append the SCOPE data with this contingency case list information.
- 6) Set flag to determine correct voltage change limits. A 6% or 12% voltage change limit should be applied depending on whether the contingency case relates to a single or double circuit outage.

After completing the above steps a full SCORPF could be performed on the resulting SCOPE data. The EVOT process shown in Figure 7-3 was used to solve the SCORPF problem. Results derived from the real-time network data using this SCORPF process are presented in the following section.

7.6.2 Results

The SCORPF results presented in Table 7-4 were obtained using a state estimator snapshot taken on 19th March 2009 at 19:06. The data preparation process described in the above section was utilised and an SCORPF method similar to the one used by the EVOT tool was applied.

Prior to the optimisation constraint limits were placed on the reactive power flow across each generator transformer, see section 6.3 for further explanation of this technique. Each of these constraint flow limits was set equal to the power flow in the initial study and scaled by the multiplier value shown in the first column of table 7-4, which is labelled 'Q-Flow Constraint Multiplier'. Reactive utilisation reduction is favoured by applying a smaller multiplier value.

The maximum active losses reduction achieved was 1.75%, which is equivalent to an annualised carbon dioxide emissions reduction of 60,000 tonnes, and the maximum generator reactive utilisation reduction was 21.5%. The SCORPF

managed to converge with a multiplier of 0.6, however the SCORPF process had to allow a number of voltage constraint limits to become soft. The best solution depends on the preference for reducing either losses or reactive utilisation, see section 6.6.

Q-Flow Constraint Multiplier	Losses Reduction	Reactive Utilisation Reduction	Notes
1	1.75%	1.91%	
0.9	1.25%	9.71%	
0.8	1.04%	16.71%	
0.7	-2.16%	21.50%	
0.6	-6.98%	31.18%	5 voltage violations

Table 7-4. SCORPF results from 19th March 2009 state estimator snapshot.

Figure 7-7 shows the effect on the voltage profile when SCORPF is applied with a constraint multiplier of unity using a state estimator snapshot that was taken on 19th March 2009. The results shown in table 7-4 show that the losses and the generator reactive utilisation were reduced by 1.75% and 1.91% respectively. These results confirm the findings of Rabiee and Parniani [111] that active loss minimisation generally increases the voltage profile. The left side of Figure 7-7 presents voltages in the north and the right side of the figure presents voltages in the south. These results suggest that an optimal voltage profile generally increases from north to south, but drops in the south west peninsula. The SCORPF achieved these results by:

- Increasing voltage targets at the HV side of generator transformers by an average of 1.9 volts. No voltage targets were decreased.
- Increasing the output of nine SVCs by an average of 61 MVar.
- Decreasing the output of twelve SVCs by an average of 37 MVar.
- Switching in three reactors and switching out six reactors at different sites. (out of 111)
- Switching in seven capacitors and switching out seven capacitors at different sites (out of 130)

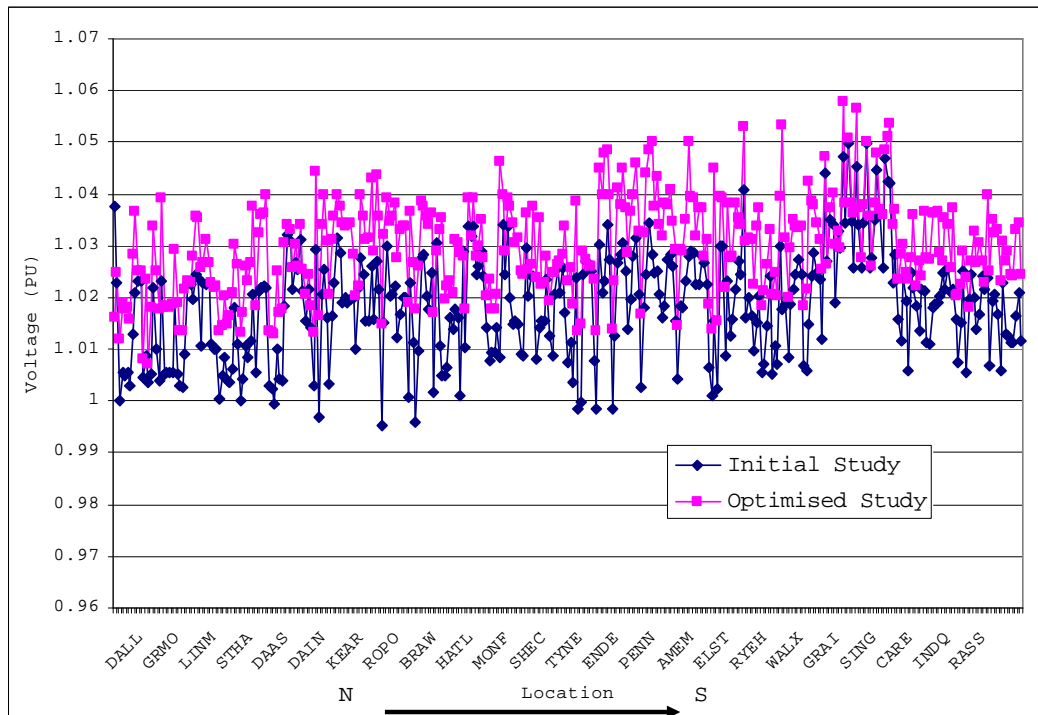


Figure 7-7. Real-time SCORPF results from 19th March 2009 state estimator snapshot.

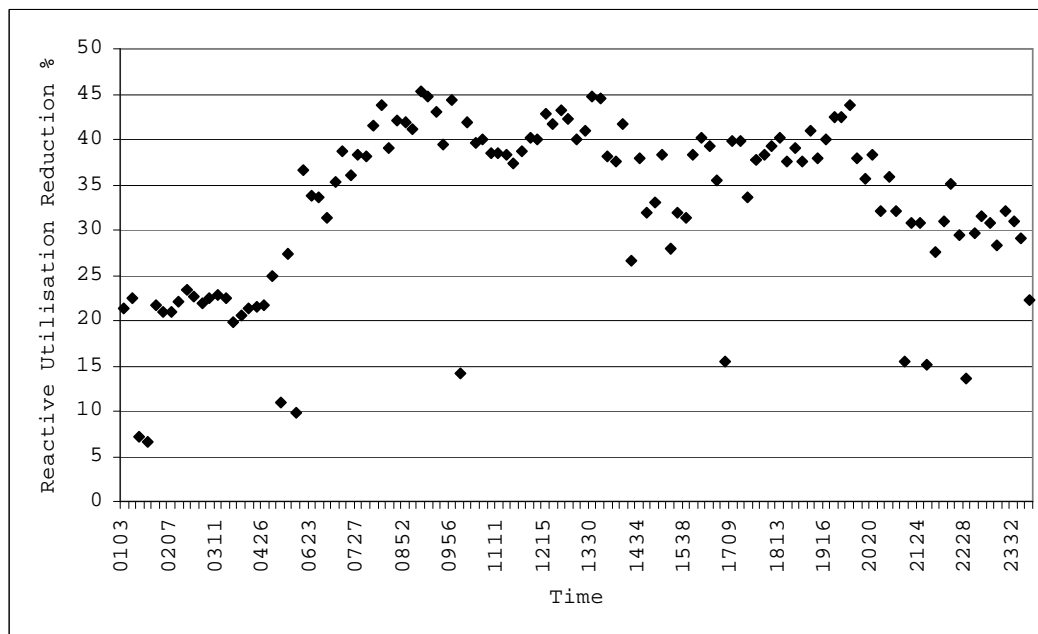


Figure 7-8. Real-time SCORPF reactive utilisation results obtained from state estimator snapshots during the 14th September 2009.

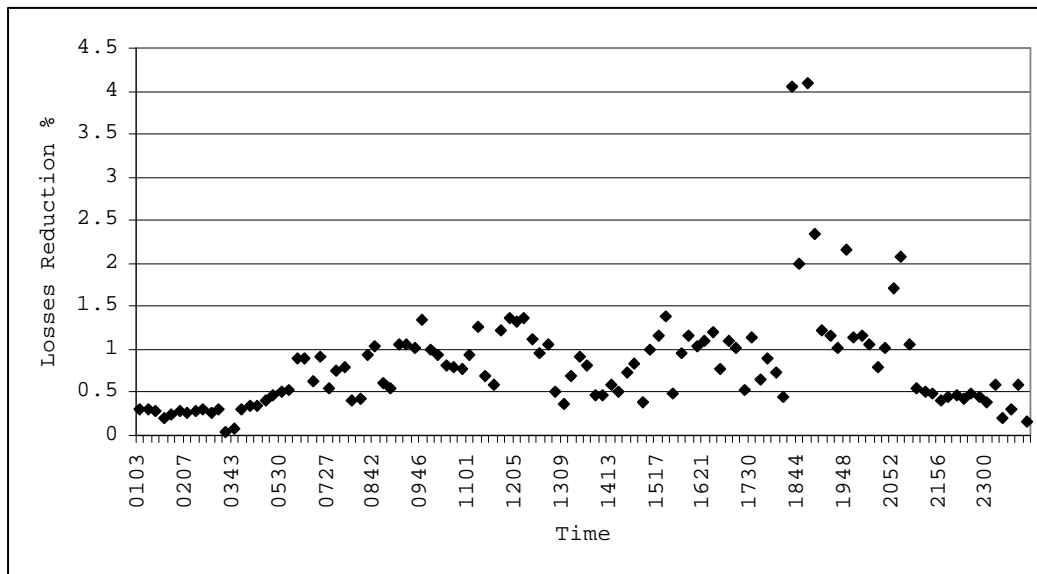


Figure 7-9. Losses reduction results using same data as Figure 7-8.

Figure 7-8 shows real-time SCORPF results determined from real-time network snapshots representative of the 14th September 2009. The results indicate that the SCORPF process is able to reduce the generator reactive utilisation at all points during the day. The results also indicate that the potential for SCORPF to reduce generator reactive utilisation roughly follows the daily demand cycle. It is interesting to note that there are two distinct bands of results in Figure 7-8, one with generator reactive utilisation reductions from 20% to 45%, and another with reductions from 7% to 16%. The results that fell into the lower band appear to be caused by the SCORPF encountering more critical contingencies. This was revealed through analysis of the convergence record. The SCORPF process managed to converge for every point shown in Figure 7-8, but had to allow some intact network and contingency case network constraints to become soft. The majority of those soft constraints were already being violated in the original network and were therefore deemed acceptable violations in practice. The SCORPF process seemed to experience greater difficulty with this real-time network data than the offline network data. The real-time network data had more violating or close to violating constraint limits, which tended to make the optimisation more difficult since the LP had to enforce more constraint limits. Figure 7-9 presents losses reduction SCORPF results from the real-time network snapshots where the optimisation is weighted towards minimising losses. These

results indicate that losses can be reduced at all times throughout the day, particularly in the middle of the evening.

7.7 Research Activity

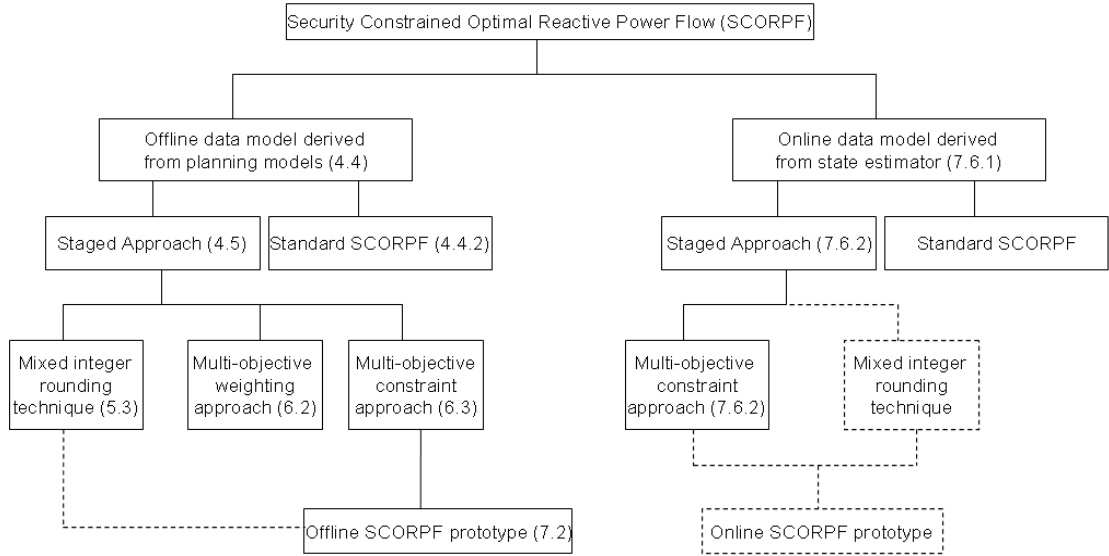


Figure 7-10. Research areas included in this thesis with corresponding section number. Dashed lines indicate future areas of research.

The techniques and results that were presented in chapters 4 to 6 provide a foundation for the development of both online and offline operational SCORPF tools. Figure 7-10 summarises the research achievements that were presented in this thesis and indicates that they could be developed into a prototype SCORPF tool. For example the mixed integer rounding technique could be included in the offline SCORPF prototype tool to improve the objective function reduction, but before this can be implemented the technique must be developed so that it is compatible with the multi-objective optimisation process. Other potential areas of future research will be discussed in section 8.5.

7.8 Summary

A secure, effective and robust control centre SCORPF prototype tool has been described. The ACCORD tool presented by Lee [71] and Dandachi [17] demonstrated the possibility of using SCORPF in control timescales, but the tool suffered from several practical limitations. The EVOT tool presented in this chapter has managed to overcome many of these issues. EVOT is able to reliably

determine SCORPF solutions that are secure against 800 credible contingency case events, while ACCORD could only guarantee that the solution was secure against 20 contingency case events. EVOT was able to converge securely for a wide range of different network conditions without any manual intervention during the optimisation process. The solutions from the EVOT tool confirmed the validity of some of the existing National Grid voltage control practices such as the importance of maintaining a high voltage profile around the London area of the network. However the EVOT tool also suggested that alternative practices need to be considered in relation to exploiting network gain and maximising generator reactive reserves.

When ENCC engineers were presented with an EVOT network optimisation solution it was sometimes deemed necessary to perform additional manual adjustments to achieve a more desirable network voltage profile, however this was found to be highly dependent on their individual engineering judgement. The changes that were intended to reduce the objective function value actually caused a global increase.

Feedback from ENCC engineers relating to EVOT version 2 can be used to shape a future practical SCORPF tool. Such a tool would need to be fully secure against all credible contingency cases at multiple points in time, rather than just being secured around a snapshot in time. This could be achieved by incorporating additional time-linked constraints into the optimisation. ENCC engineers have also indicated that an ideal tool should not only be able to determine the optimal reactive dispatch of an offline study, but should also instruct ENCC engineers on how to evolve the network from its current configuration towards an optimal configuration. SCORPF results that are based on real-time network data have been presented in this chapter. The results from this study indicate that there is significant potential for secure active losses reduction and secure generator reactive utilisation reduction during the real-time operation of the network.

This chapter has indicated some of the potential issues of utilising SC-ORPF for operational use. Possible the most important of these issues is the lack of confidence that has been historically associated with these tools due in part to

their black box nature. Other issues exist such as ensuring that the output from the tool is both useful and meaningful to control centre engineers. However, this chapter has demonstrated that progress has been made in addressing both of these concerns.

This chapter has presented details of the methods, results and feedback from different SCORPF implementations that solve the mixed integer non-linear reactive dispatch problem. These implementations are based on the idea of first solving the SCORPF problem treating all controls as continuous and then rounding off discrete controls to their nearest value. As described in chapter 5 this approach can occasionally cause sub-optimality and infeasibility in the solution, hence it is possible to improve the prototype SCORPF tool by incorporating the probabilistic shunt switching logic that was introduced in section 5.3.

Chapter 8

Conclusions and Future Work

A number of significant advances in the field of SCORPF and operational active losses management have been made as a result of this research, which is important given the climate change targets that the UK has committed itself to achieving. The research has applied a SCORPF technique to GB transmission network models that include a large number of contingency cases. These SCORPF studies, with the active transmission losses minimisation objective, produced on average a 1.9% reduction in losses, which is annually equivalent to abating 64,000 tonnes of CO₂ emissions. To achieve these results this research project has had to develop a framework for modelling and executing the SCORPF, which has led to the development of novel techniques and processes.

Firstly a novel three staged SCORPF technique was developed, which works by applying a preconditioning stage of intact network optimisation, before executing the remaining SCORPF stages. The results that were presented in section 4.5.4 indicated that a significant improvement over the standard single staged approach was achieved. Secondly a constraint based technique for solving multi-objective SCORPF was devised. Over a range of GB transmission network conditions this technique generated solutions that had a smaller standard deviation in their objective function improvements than the corresponding solutions from the standard weighting technique [30]. In addition the constraint based multi-objective SCORPF technique managed to produce the following improvements in ENCC solutions:

- Lower active losses
- Lower reactive costs
- Lower reactive utilisation
- Greater generator reactive reserves
- Improved voltage margin

With these techniques it was then possible to develop a prototype voltage optimisation tool for the ENCC called EVOT. Feedback from ENCC engineers has indicated that the EVOT tool is able to rapidly produce solutions that have lower reactive utilisation and active losses, while maintaining the required level of network security. This success has managed to create a greater confidence in voltage optimisation technology amongst engineers and managers. Implementation of this technology now forms a key part of National Grid's overall operational voltage control improvement strategy, because the technology is considered to have a crucial role to play in the voltage management on the 2020 transmission network.

A technique was also developed to improve the active transmission losses objective function reduction when solving the GB transmission network voltage optimisation problem with large switchable shunt devices. This is a mixed integer optimisation problem, since the optimal values of both continuous and discrete control variables need to be determined. The standard approach for handling these discrete variables, in commercial software and in the literature, is to assume that all discrete controls can vary continuously [84] and then perform a final stage of rounding. A probabilistic shunt rounding technique was proposed in section 5.3, which manages to achieve a lower loss solution than the standard technique, and therefore provides an alternative approach for handling discrete control variables.

These techniques and the EVOT tool have been the subject of peer reviewed journal and conference papers [21, 20, 19, 23, 22, 112]. This research has also resulted in several new features being incorporated into a popular commercially available SCORPF tool.

In addition some of the major findings of this research have directly fed into other projects at the ENCC specifically a six-sigma Voltage Control Improvement (VCI) project. The main objective of the VCI project was to implement process improvements in the ENCC voltage despatch process to reduce costs and improve network security. The reactive utilisation reduction results that were presented in chapter 6 of this thesis were of particular importance to the VCI project, as these results were able to demonstrate the value of SCORPF based tools to the ENCC.

These results formed an important part of the final VCI project presentation, and placed SCORPF on the company roadmap for improving the voltage despatch process. Since the VCI project presentation the EVOT tool, which was described in chapter 7, has been evaluated by ENCC engineers. ENCC engineers are now planning a future project to continue this research, which will build upon the techniques developed within this project, so that improvements in the voltage despatch process can be achieved.

8.1 Large-scale SCORPF

A general shortage of published literature was identified describing the implementation of reactive optimisation technology for power system operational planning and control. The reason for this shortage is due to both the technical challenges, such as those described by Momoh et al. [89], and the human issues that need to be resolved. A number of these challenges have now been addressed by this research such as how to select credible contingency cases, how to deal with contradictory shunt switching configurations and how to interface and model the optimisation with existing systems.

Previously published work did not fully address the issue of securing a practical SCORPF transmission network problem with a large numbers of contingency case events [77, 78, 79]. In order to fill this gap in the literature the current research project has produced losses and generator reactive utilisation reduction results, which have been acquired by applying SCORPF to GB transmission network optimisation problems constrained with around 800 credible contingency case events. This research has also showed that when warm starting the SCORPF from a secure GB network operating point, the losses reduction process encounters few contingency cases with binding constraints. It was also observed that the voltage stability margin of the network could be increased by the application of SCORPF. The reason for this improvement was found to be due to the reduction in generator reactive utilisation, which meant that there were bigger reactive reserves across all generators, and hence greater network security. The reduction in generator reactive utilisation following SCORPF with the active losses objective was unexpected since this was not the objective of the SCORPF. This may have

occurred due to the sub-optimality of the initial starting point. This observation is consistent with that of Rabiee and Parniani [111], who noticed that the voltage stability margin and reactive power reserves could increase with a simultaneous decrease in losses.

8.2 Mixed Integer SCORPF Technique

A gap in the published literature was identified relating to the treatment of discrete control variables when solving the mixed integer power system optimisation problem, specifically problems involving large switchable shunt capacitor and reactor controls. The literature describes the discrete shunt switching problem as essentially remaining unsolved in a reasonable time on a complex large-scale power system [24, 25, 26, 27]. To address this issue an enhanced probabilistic technique was developed by this research to provide a solution to this problem. This technique has been shown to produce solutions that are competitive with those produced by the branch and bound based optimisation solver MINLP, and can scale up more efficiently to solve large-scale optimisation problems. The SCORPF active losses reduction that was achieved relative to the initial ENCC offline study was on average 18MW, with around 3MW of this saving being achieved by the enhanced probabilistic technique. The enhancement has managed, in effect, to increase the active losses reduction by an extra 20%.

There is likely to be an increasing requirement on transmission system operators such as National Grid to securely manage the power network, so that it is operated with low active power losses. The results that have been obtained from the enhanced probabilistic technique show that it can be used to achieve a further reduction in the active losses by improving the optimality in the dispatch of discrete shunt controls.

8.3 Multi-objective SCORPF Technique

This research has developed an alternative method for solving the multi-objective optimisation problem involving the active transmission losses and generator reactive utilisation minimisation objectives. The proposed method solves the

active transmission losses reduction optimisation problem with extra fictitious constraints on the reactive flow across generator transformers. The value of each of these constraint limits is determined from the initial reactive flow across the corresponding transformer multiplied by a user definable parameter value. It is then possible to tune this parameter to achieve a desired behaviour.

Previous published multi-objective optimisation research often formulated the objective in terms of a linearly weighted sum of the different objectives [113]. By varying these weightings it was then assumed that the Pareto optimality curve could be adequately explored. Das and Dennis [30] have shown that with the weighing method it is often the case that only a limited region of the Pareto curve is accessible and that changing the weighting values may not produce a different solution.

The research presented in this thesis has gone further by demonstrating that the standard weighting method with constant weighting values can produce inconsistent objective value improvement over a range of likely network operating conditions. The average standard deviation in the reactive utilisation improvement, over a range of network conditions, was determined. These standard deviation values were 10.1% and 27.8% for the constraint-based and standard weighting techniques respectively. The average standard deviation in the active losses objective function improvements were 1.7% and 3.2% from the two techniques respectively. The constraint-based technique's smaller standard deviation suggests that it is the more suitable of the two approaches for practical implementation in a control centre multi-objective optimisation tool, as it is more dependable over a range of different network conditions.

8.4 Prototype voltage optimisation tool

The prototype control centre voltage optimisation tool developed by this research, which was called EVOT, managed to overcome some of the problems encountered in previous ENCC voltage optimisation tools such as ACCORD. ACCORD was limited to securing the network against a maximum of 20 contingency cases, it did not include optimisable shunt controls and it suffered

from occasional non-convergence [71]. In contrast the EVOT tool can handle up to 1000 contingency cases and has a complete model of available shunt controls. EVOT was also been designed to be easy to use and to have a high convergence success rate.

The EVOT tool has given ENCC engineers direct access to a fully automated SCORPF process, allowing them to become engaged and build confidence in reactive power optimisation technology. By following a feedback-improvement cycle the EVOT tool has gradually had extra features added to it to make it suitable for practical use. The valuable feedback obtained from ENCC engineers, which was presented in sections 7.3.2, 7.5.3 and 7.5.4, demonstrates that both human and technical factors are important for the overall success of SCORPF technology.

8.5 Future work

This research has resulted in the demonstration of SCORPF technology to control centre engineers at the ENCC, who were then able to provide a substantial quantity of useful feedback. This feedback has highlighted several limitations that will need to be addressed by future research. Effective and efficient methods for performing time-linked SCORPF will need to be developed, ideally as an extension to the existing technology. Consideration will need to be given on how the solution is to be implemented, for example does full SCORPF need to be performed at all future time points and does the optimisation need to minimise the objective value at all time points simultaneously.

A time-linked SCORPF approach could be developed with existing software by performing SCORPF with the transmission losses reduction objective on a network representative of a time A . The reactive dispatch solution would then be transferred to a network representative of a future time B . SCORPF could then be performed on network B with a minimum control action objective to remove any violations, the reactive dispatch solution would then be fed back into network A . Finally SCORPF would be performed on network A with a minimum control action objective to remove any new violations. If the removal of violations on

network *B* did not create any new violations in network *A* then the solution would be secure for all time points. Conversely, if violations were created then the final solution from this process would represent a solution that is secure at time point *A* and would need a minimum number of control changes to ensure continued security at time point *B*. The advantage of this method is that it could be extended to secure a number of different time points, while considering a large number of contingency case events. The disadvantage of this method in its current form is that it minimises the objective function at a single point in time.

Feedback has also revealed that a practical SCORPF tool should not only be able to derive optimised studies that are secure against a number of contingency case events and future network conditions, but it should also be able to produce minute by minute advice on how to implement the optimised reactive dispatch. One method of doing this would be to develop optimised offline network targets using a process that is based on EVOT. This target information would then be fed to a reactive dispatch program that interfaces with the state-estimator to advise the Transmission Dispatch Engineer of which reactive equipment to switch and when to do it. The reactive dispatch program would determine a trajectory to develop the network from the current operating point towards a target operating point, with switching decisions being made on the basis of maintaining network security. Taylor et al. [114] made the assumption that continuous variables could be dispatched without reference to other time points, as they can be adjusted more frequently than discrete variables. If we make the same assumption then it would only be necessary to use the optimised offline targets to make discrete switching decisions. Eventually, once confidence has been established by control engineers and management, the process could be partially automated.

A novel mixed-integer SCORPF technique was developed within this research. Future research should now determine if a similar technique could be utilised to obtain an improvement when solving the multi-objective SCORPF problem. This research should consider not only discrete shunt devices, but also discrete transformer taps. Finally, studies should also be performed to determine whether the technique can be applied successfully to solve other mixed integer power system optimisation problems.

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